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# STRIATIONS IN *rf* DISCHARGES AND *dc* DISCHARGES WITH *rf* PERTURBATIONS

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# STRIATIONS IN rf DISCHARGES AND

# dc DISCHARGES WITH rf PERTURBATIONS

by

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## ABSTRACT

A study of striations in the rf glow discharge and the dc discharge with rf perturbations was conducted in neon gas over an rf frequency range of 1.5 MHz to 12 MHz and a pressure range of 1 to 15 torr. The striation parameters were measured in a variety of situations and a study was made of (1) stationary striation phenomena, to include the parameters of the rf discharge, the effects of the induced rf electric field and the limitations imposed by the power input to the field, (2) the relation between the striation wavelength and the longitudinal electric field and (3) the relation between the electron temperature and the longitudinal electric field. The utilization of an rf perturbation allowed a study of rf discharge phenomena and gave a method whereby power could be put into the discharge by a means other than the dc electric field. The results of the experiment indicate (a) that stationary striations may be a standing wave phenomenon (b) the wavelength of moving striations is not uniquely determined by the electric field (c) more work and analysis is necessary concerning the relationship of the electron temperature and the longitudinal electric field.

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# 1. Introduction

## 1.1 Background

The field of plasma physics has grown rapidly in the past twenty years. The study of plasmas has contributed knowledge to the fields of thermo-nuclear processes, radio communications, space propulsion, astrophysics and many others. Its importance is unquestioned.

The term plasma was originally defined by Langmuir and Tonks [1] in the following words:

> the word 'plasma' will be used to designate that portion of an arctype discharge in which the densities of ions and electrons are high but substantially equal. It embraces the whole space not occupied by the sheath.

Present indications in the field of thermo-nuclear fusion devices imply that the most promising source of a controlled fusion reaction is in a plasma at high temperatures. To date, it has been impossible to maintain sufficient stability of a plasma to sustain the necessary temperatures. It has become readily apparent that a basic understanding of the inherent instabilities of a plasma is of utmost importance.

This implies that a basic theory of a plasma is needed. At the present time, no adequate theory exists. Since moving striations are an inherent instability of the plasma of a positive column, no theory would be correct that did not explain their existance. They are perhaps the best known but least understood instability in plasmas.

Although the phenomenon of moving striations has been known for over a century it has only been since the early

twenties that a major research effort in this area has been carried out. Most texts and journals prior to that time either avoid the subject entirely or mention it only in passing. There have been many attempts to explain moving striations in very recent years, but today an adequate theory to satisfactorily explain their existance is still lacking. The difficulty of the subject is shown by the fact that there exist several forms of striations and their properties are sensitive functions of the discharge parameters.

In the past fifteen years, major advances have been made in this field by L. Pekarek, H. S. Robertson, A. W. Cooper, N. L. Oleson, K. Wojaczek, M. Novak and others.

Moving striations, a common phenomenon, exist over a wide range of pressures, currents and tube sizes. They can even be induced in an otherwise homogenous column by external radiation, by the applications of external electric or magnetic fields, or by other oscillations [12] .

In a low pressure gas discharge the positive column is frequently alternately striated by bands of high and low light intensity which are called striations. Striations may be stationary or moving. Their motion depends on such parameters as electrode configuration, tube geometry and type of gas.

The moving striations are normally found in low pressure, low current rare gas discharges. They usually travel to the cathode with velocities from 10 to 1000 m/sec., but they have been observed by Donahue and Dieke [3] to travel toward

the anode and on occasion to travel in both directions simultaneously. Those traveling toward the cathode are called positive striations and those traveling to the anode are called negative striations. Due to their velocity, moving striations are not visible to the naked eye. They are normally detected by use of photomultiplier tube-oscilloscope circuitry.

The wavelengths of the striations are dependent on tube geometry. In general, they are a few times larger than the diameter in a cylindrical tube and normally less than the length of the positive column.

Moving striations are not small signal fluctuations but are associated with large fluctuations of electric field intensity, electron temperature, discharge potential and current.

A very complete and thorough analysis and history of moving striations by Cooper and Oleson is now in the process of publication [12] . It appears to be the only publication of its kind in print and is highly recommended to anyone working in the field of moving striations.

Standing striations can be seen by the naked eye as spherical regions of light intensity. Standing striations occur very frequently in rf discharges and will be discussed in more detail later in this paper.

### 1.2 The Glow Discharge [4]

When a cylindrical tube containing gas which is normally an insulator, at pressures below a few centimers of mercury

has a sufficiently large potential applied across it, a glow will be produced throughout the major portion of the tube. The glow is caused by electron transitions in the atoms which are due to excitation and ionization of the gas molecules by the bombarding electrons. If the pressure is lowered to the millimeter region the discharge will consist of alternate dark and light spots, which are spaces of different luminosity in the glow discharge. They are not striations and should not be confused with these. The size and intensity of the alternate dark and light spaces are determined by the potential across the tube, the pressure in the tube, the current and the type of gas. The shape of the cathode region is determined by the cathode shape. Figure 1 shows the regions and spacial distribution of light intensity in a normal glow discharge. It should be noted that the dark spaces are not completely devoid of light but are dark only relative to bright regions where ionization and excitation processes are much more active.

The positive column is so named because it is at a potential close to the anode. It does not support a strong electric field. Although normally it is the largest part of the discharge its presence is not a requirement for maintaining a glow discharge.

The axial electric potential gradient $\frac{dV}{dx}$ can be found, as was done in these experiments, by placing two probes in the positive column a known distance apart and measuring the difference in potential between them. Since $\frac{dV}{dx}$ is

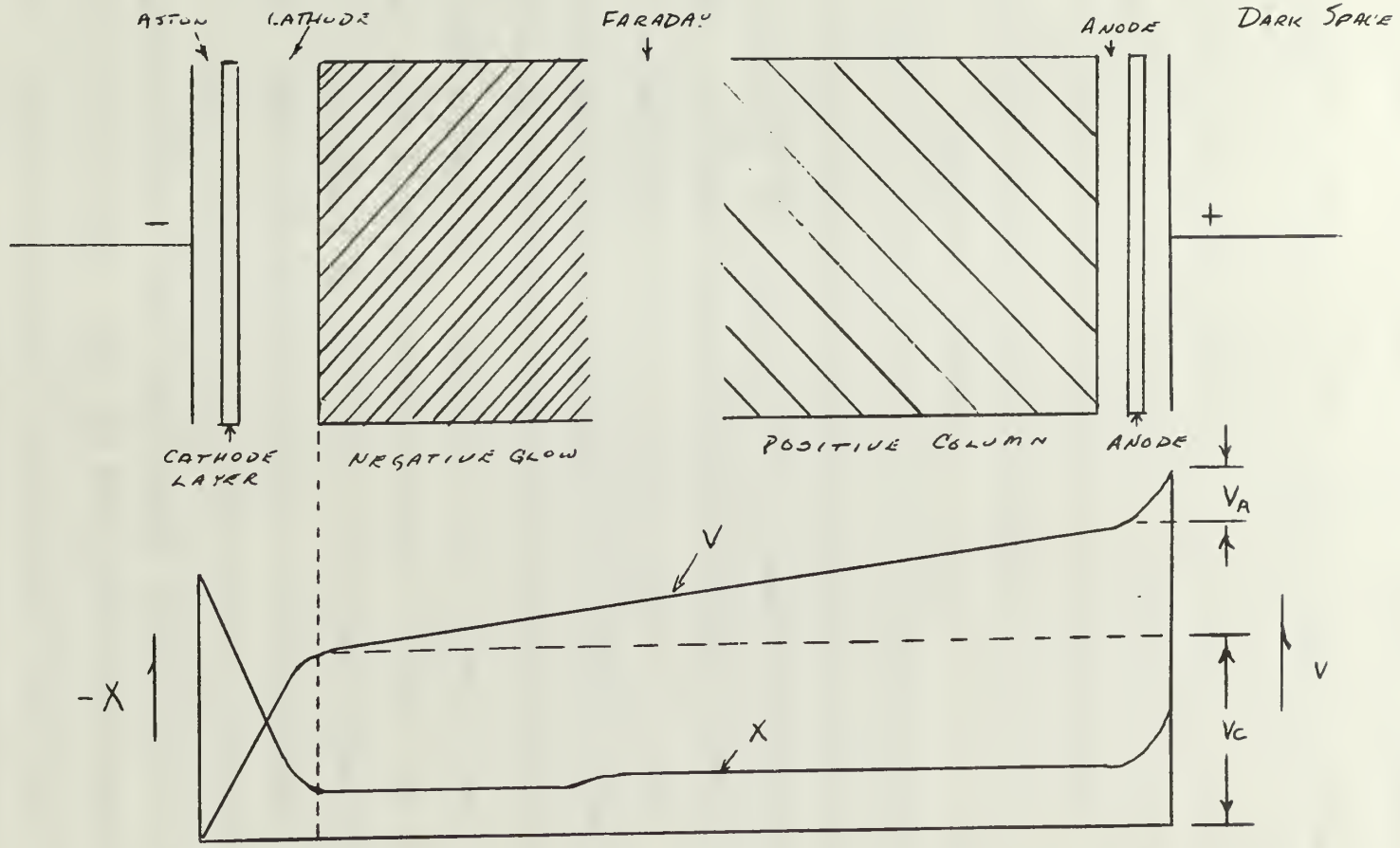



Fig. 1. Regions and spacial properties of a glow discharge.

approximately constant, $\frac{d^2 V}{dx^2}$ equals zero. We know from Poissions equation that $\nabla^2 V = -4\pi\rho$. Therefore $\frac{d^2 V}{dx^2} = 4\pi(\rho^+ - \rho^-) = 0$, and hence densities of negative and positive particles in the positive column are almost equal. In the uniform column the electric field must have a value such that the number of electrons and ions produced per unit time just balances the loss of charge.

It is felt that the processes of ionization and excitation which take place in a glow discharge are of sufficient importance to warrant a discussion at this time. An excited atom is one in which an electron has been lifted from a lower to a higher energy level. The increase in energy may be due to collisions with neutral particles or it may be due to interaction of the atom with the electric field of an incoming ion or electron. Excitation may also occur as the result of absorption by the atom of a photon with the correct energy. If the energy transferred to the atom is larger than the ionization potential, then ionization will occur; if it is less, excitation occurs. An electron in the higher energy level will normally remain in that state for about $10^{-8}$ seconds, before falling to a lower state with emission of a quantum of energy in the form of radiation. This process is called spontaneous emission. In some cases the electrons may be excited to an energy level for which the probability of transition to a lower level by spontaneous emission is very small.

This is a metastable state which can last in excess of $10^{-2}$ sec. Generally they are destroyed within this time. Normally, metastable atoms occur among lower energy levels since there are fewer levels that the electron can fall into. Metastable atoms have been linked to moving striations in the discharge; however, it has not yet been determined exactly how the metastable atoms influence the excitation of moving striations.

There are three types of glow discharges, the normal, subnormal, and abnormal discharge. The potential drop across a discharge tube is shown as a function of current in Fig. 2. Figure 2 also shows the regions where the three types of discharge exist.

A very detailed and excellent description of the glow discharge and the internal processes concerned is presented by Francis [5].

1.3 The rf Discharge [6]

It has been known for about sixty years that a gas can be made conducting when placed in a rapidly alternating electric field. A systematic study, however, did not begin until about 1920. Low pressures and frequencies of a few megacycles were used. Most of the work performed in this period dealt with investigation of the starting potential and its variation with the pressure and type of gas, the frequency of the field and the electrode separation. The geometry is an important factor in high frequency discharges. There are many different arrangements possible and it is

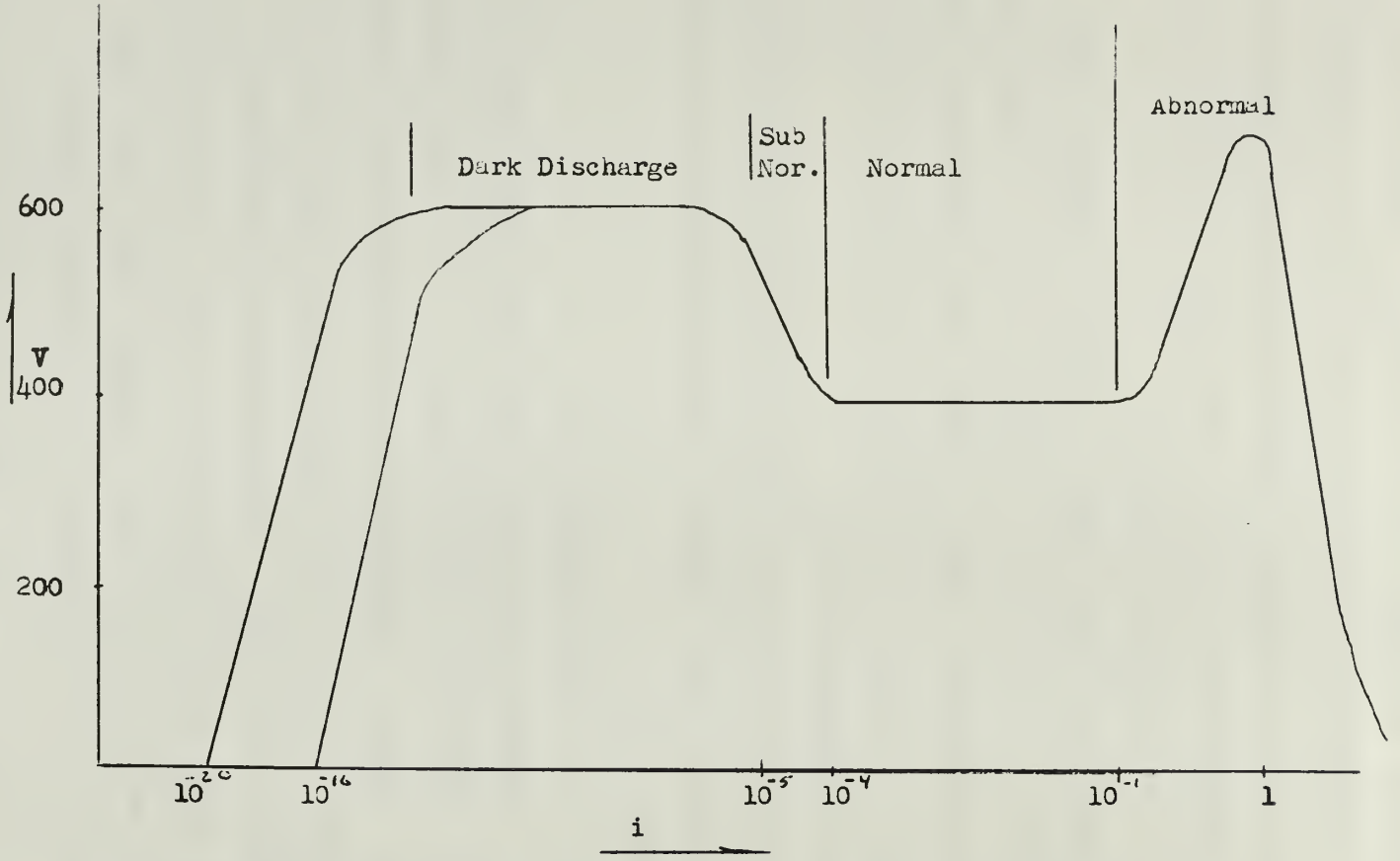



Fig. 2. Maintenance potentials of the three main types of discharge.

important to distinguish between the types because the properties of the discharge can be quite different.

The most commonly used arrangements are:

(1) Parallel plate electrodes, either internal or external or coaxial cylindrical electrodes, which give a known electric field.

(2) A solenoid carrying an oscillating current wrapped around a discharge tube.

(3) A resonant cavity for fields of very high frequencies in the microwave region.

Early workers in this field thought the high frequency discharge to be analogous to the dc glow discharge. Each electrode was thought to act as an anode and cathode in alternate half cycles. At higher frequencies Townsend and Gill [6] showed that the electrodeless discharge in long tubes resembled the positive column of a dc discharge. They postulated that the only difference was in the ionization effect which was due to the motion of the electrons in an alternating field. J. Thompson [7] subsequently developed a simplified theory in which he considered the motion of free electrons in the gas. He stated, as a condition for breakdown, that the electron must acquire enough energy to ionize and must hit a gas molecule before this energy can be returned to the field. J. J. Thompson used a similar idea to explain an electrodeless ring discharge. Both of these theories give a good qualitative picture of the properties of the discharge but fail to predict correct values for the parameters.

There are three major ways in which ionization in an alternating electric field differs from ionization in a steady dc electric field.

(1) Because of the periodic reversal of field direction, the charges may not be swept on to the walls. This implies a reduction in the loss of charge, hence low fields lead to a slow growth of ionization which results in an equilibrium conduction state i.e. a self sustained discharge.

(2) Charged particles, photons and excited atoms striking the wall cause secondary emission but these electrons do not contribute to the growth of ionization unless they are emitted when the field is in the right direction.

(3) Alternating discharges can be produced in insulating vessels and the drift of ions and electrons to the wall sets up transverse fields which control the density of ionization in the space.

Francis [6] lists three factors which determine the breakdown field and subsequent current and ion densities of the discharge.

(1) The gas pressure, and consequently the mean free path of the electrons and the frequency of collision with gas molecules.

(2) The frequency of the applied electric field X, where

$$X = \underline{X}_o \sin \omega t = \underline{X}_o \sin 2\pi ft$$

(3) The dimensions of the vessel; for the tubes used in this experiment these would be the length in the direction of the electric field and the radius.

In the rf discharge in a gas at low pressure ($\lambda_e < d$) the frequency of collision is much less than the frequency of the oscillating electric field. An electron at $x = 0$ with an initial velocity $v_o$, in the direction of a

uniform electric field, has the following equation of motion

$$m \frac{d^2x}{dt^2} = e\mathcal{E}_0 \sin(\omega t + \phi)$$

where $\phi$ is the phase angle of the field at time t = 0, ie, when the electron starts. Integration and application of the boundary condition $\frac{dx}{dt} = v_0$ at t = 0 gives the velocity at time t as

$$v = v_0 + \frac{e\mathcal{E}_0}{m\omega}\left[\cos\phi - \cos(\omega t + \phi)\right]$$

correspondingly the displacement in the direction of the field will be

$$x = \left(v_0 + \frac{e\mathcal{E}_0}{m\omega}\cos\phi\right)t + \frac{e\mathcal{E}_0}{m\omega^2}\left[\sin\phi - \sin(\omega t + \phi)\right]$$

Thus it is clearly shown that there exists a steady drift velocity at uniform speed in the direction of the original velocity upon which is superimposed a sinuousoidal occillation with amplitude $\frac{e\mathcal{E}_0}{m\omega^2}$. Any initial motion perpendicular to the field will remain unchanged.

Since the velocity consists of a constant plus an oscillating component it will not absorb any power from the field (if there are no collisions). The steady component of the velocity will absorb energy from and return it to the field in alternate half cycles.

The general motion of an electron in an electric field is shown in Fig. 3.

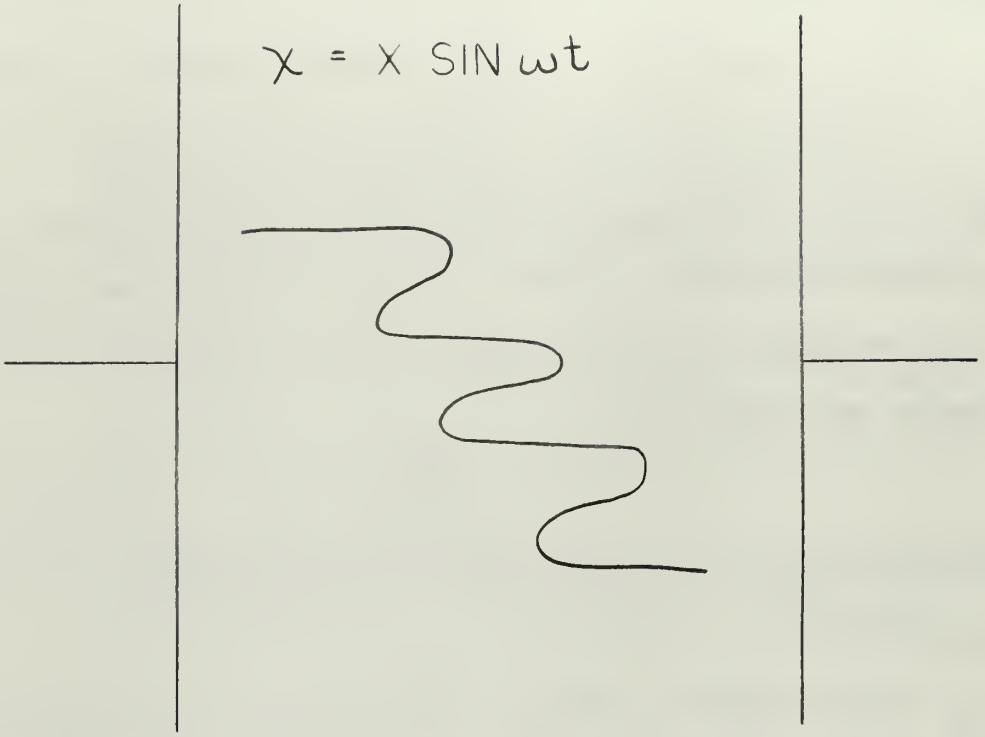



Figure 3. Motion of an electron in an oscillating electric field. [6]

1.4 Langmuir Probe Theory

It is deemed appropriate to discuss briefly the theory behind electric probes in view of the fact that measurements made in the course of these experiments utilized electrostatic probes. The discussion will be presented in two parts, the first concerning the single probe technique and the second concerning the double probe technique. In addition the discussion will be limited to the characteristics of cylindrical probes in weakly ionized plasmas in the absence of magnetic fields since this is the situation that existed during these experiments.

The technique of probe measurements was developed by

Langmuir [10] in 1924 and hence the method is appropriately named after him. A probe is simply a metal wire which is inserted into the plasma. It is connected to a voltage source which can be used to bias the probe at various voltages both negative and positive with respect to the plasma. If the electron current to the probe is plotted as a function of probe voltage, a curve similar to that shown in Fig. 4 will be obtained.

The point marked $V_s$ represents the point at which the probe and the plasma are at the same potential. This point is generally called the space potential. At this point the probe collects predominantly electron current due to the fact that there are no electric fields and the electrons move much faster than the ions. At the point $V_f$ the probe, which is at floating potential, draws no current. This implies that flux of electrons equals the flux of ions. If the probe is biased negatively as in region A almost all electrons are repelled and at the same time the ions are accelerated forming an ion sheath around the probe, which leads to ion saturation current. In a similar manner, if the probe is biased positive as in region C, the electrons will be attracted to it forming an electron space charge sheath around it. This of course leads to saturation electron current. There exist three major points of asymmetry between the saturation ion current and the saturation electron current. The first is the mass difference which causes a difference in the absolute magnitudes of the

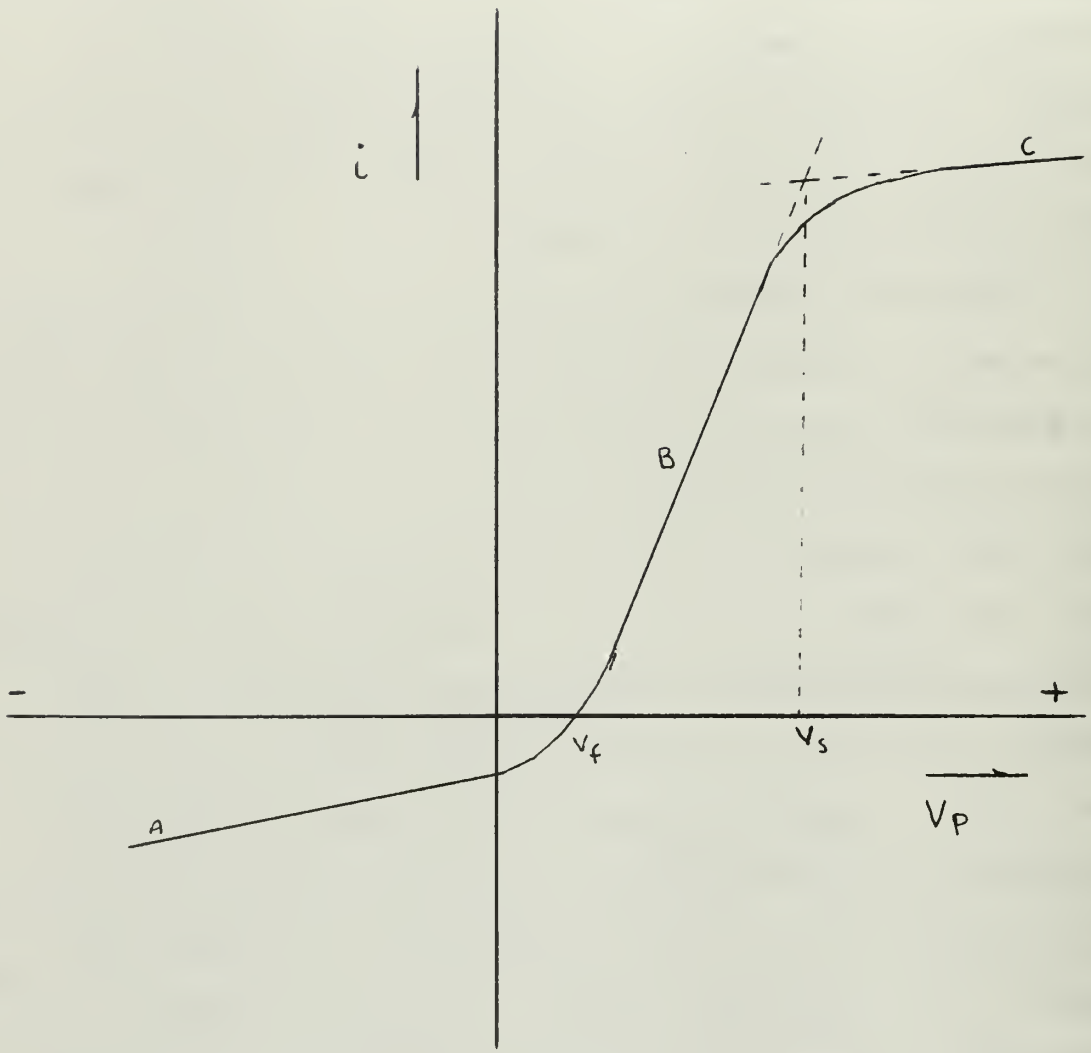



Fig. 4. A typical probe current-voltage characteristic.

currents. The second is that the ion and electron temperatures are unequal which leads to different sheath formations. The third point is that if a magnetic field is present it will influence the motion of the electrons more than the motion of the ions.

If the probe does not disturb the plasma too much it is possible to obtain electron densities and temperatures from the probe characteristic curve. In an excellent review of electric probes Chen [9] shows that if the logarithm of the current is plotted against voltage a curve similar to that of Fig. 5 will be obtained if the electron distribution is Maxwellian. The slope of the line is e/kT and gives a good measure of the electron temperature. The curve can also be used to determine the space potential as shown in Fig. 5.

The double probe method of obtaining electric probe characteristics was developed by Johnson and Malter [11]. In this method two probes placed in the plasma within a correlation length of each other are biased with respect to each other but insulated from ground. The system floats with the plasma. Figure 6 shows a simple circuit designed for this purpose. It can be seen from Fig. 7 that the two probes are always at an equal potential (but of different polarity) with respect to the floating potential.

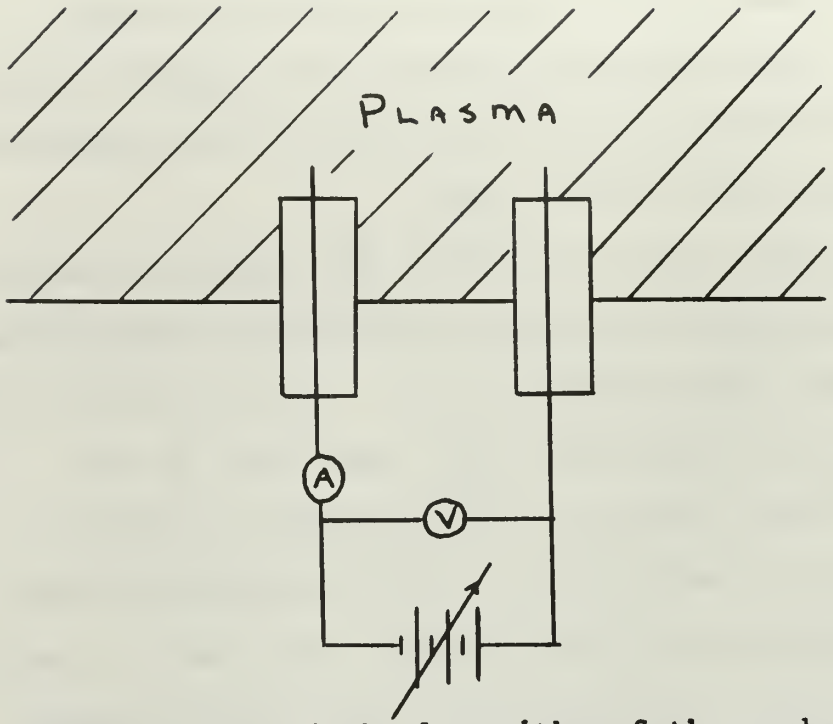



Fig. 5. Plot of the logarithm of the probe current versus voltage

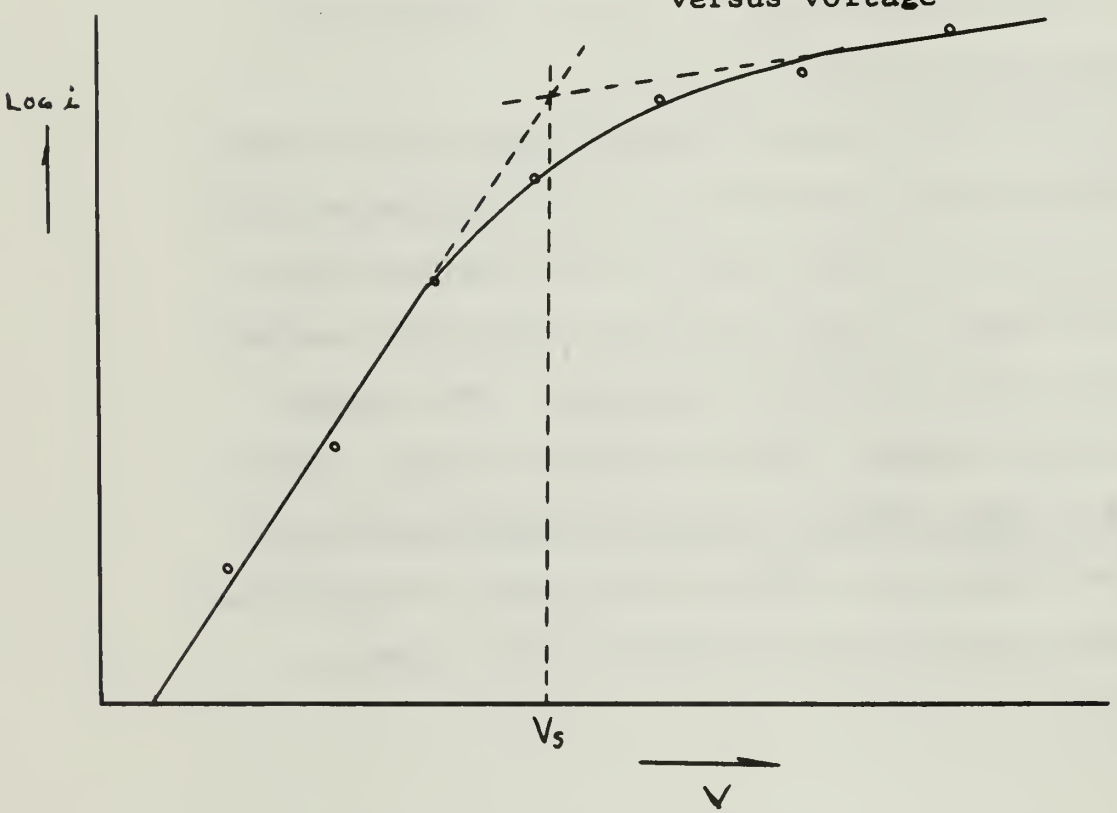
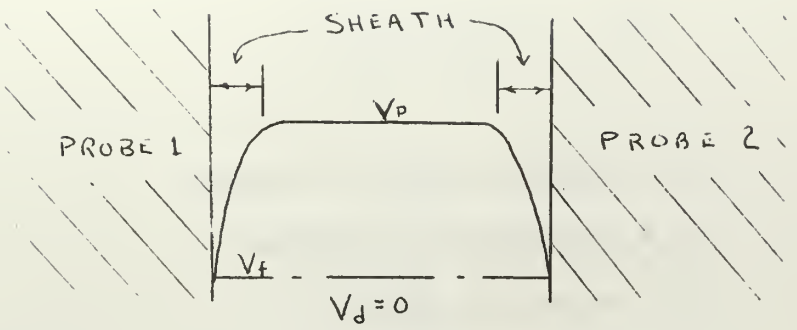
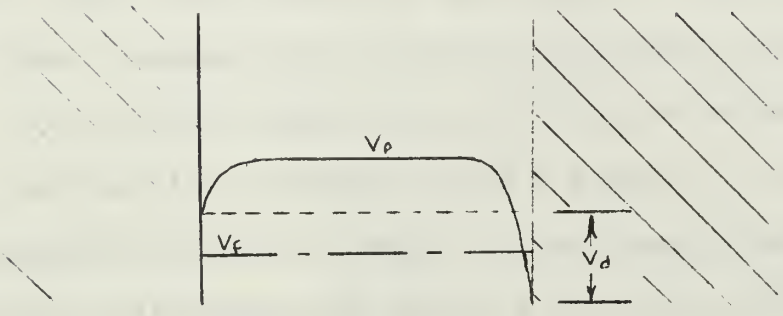



Fig. 6. Basic double probe circuit

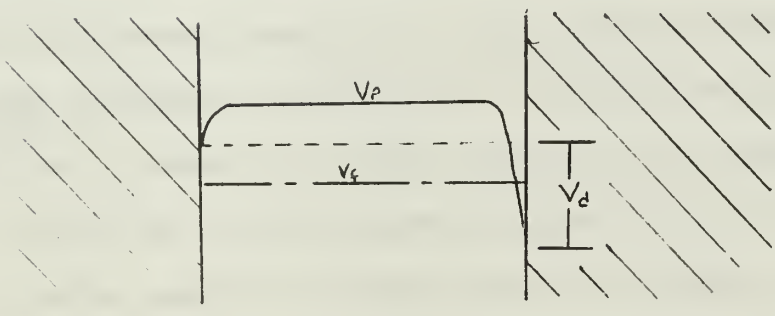



(a)




$V_d$ = SMALL NEGATIVE VOLTAGE

(b)




$V_d$ = LARGE NEGATIVE VOLTAGE

Fig. 7. Potential distributions for a double probe configuaration.

The thickness of the sheath is of the order of a Debye length

$$\lambda_D = \sqrt{\frac{\epsilon_o K T_e}{e^2 n_e}}$$

Where $\epsilon_o$ = permittivity of vacuum

$K$ = Boltzmann's constant

$e$ = electron charge

$T_e$ = electron temperature

$n_e$ = electron density

When $V_d = 0$ (see Fig. 7a) each probe will collect zero net current from the plasma and the current i will be zero corresponding to point 0 on the curve of Fig. 8.

When $V_d$ equals a small negative voltage the potentials will adjust themselves in order to satisfy Kirchhoff's law, [11] . The system will assume the potentials shown in Fig. 7b. From this we can see that probe 1 moves closer to the plasma potential and hence draws more electron current while probe 2 moves further from the plasma potential and draws less electron current. The current flowing to probe 1 will pass through the external circuit to probe 2 and the system will be located at some point a, on Fig. 8.

If $V_d$ equals a large negative voltage, probe 1 will move even closer to plasma potiential and probe 2 will move further away. Probe 1 will draw all the electron current and probe 2 will draw none. The current flowing to probe 1 will pass through the external circuit to probe 2 and the system will be located at some point b on Fig. 8.

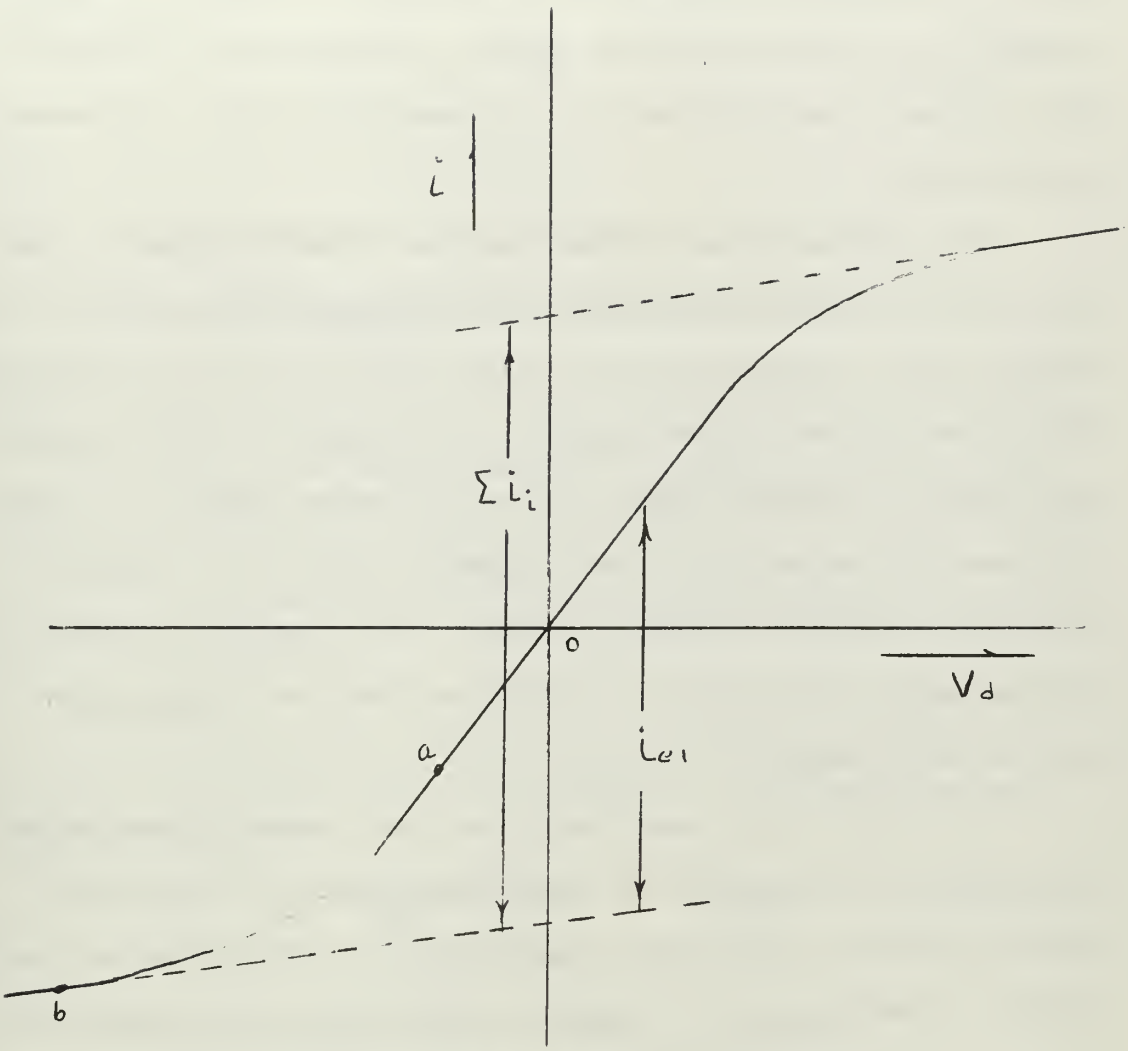



Fig. 8. Double probe characteristic curve.

If $V_d$ is made more negative it will have no effect since probe 1 already collects enough electron current to balance the ion current to the system, hence the current is limited by ion saturation current to the negative probe. Due to symmetry the upper portion of the characteristic curve in Fig. 8, will be obtained if the potential V is increased positively.

The double probe method has one disadvantage in that the bulk of the distribution is not sampled, because in this method only electrons in the high energy tail are collected. There are however, two distinct advantages of this method over single probe methods; first and most important there is less perturbation of the plasma since no net current is drawn from the plasma; secondly the laborious process of making semi-log plots to determine electron temperature can be eliminated.

In view of the fact that electron temperatures were measured in the course of this experiment by the double probe method it is deemed appropriate to show the derivation of the formulae used. Detailed derivations are given by Johnson and Malter [11] and by Chen [9].

Since the system is floating the net current must be zero. Therefore

$$i_{i1} + i_{i2} = \sum i_i = i_{e1} + i_{e2}$$

where these terms represent the electron and ion currents to probes one and two at any given potential $V_d$. The electron density at the probe surface obeys the Boltzmann

distribution. Therefore the electron current collected by probe 1 is

$$i_{e1} = A_1 j_r e^{-eV_1/kT_e} \qquad (1.1)$$

and similarly

$$i_{e2} = A_2 j_r e^{eV_2/kT_e} \qquad (1.2)$$

where $A_i$ = area of the probe

$j_r$ = random electron current density

$V_i$ = potential of the probe with respect to the plasma.

These formulae point out a basic assumption in the theory, ie, the probes are always negative enough to collect saturation ion current. This implies that $\sum i_i$ can be determined from the probe characteristic curve as shown in Fig. 8.

Since only a few electrons are sampled a measure of $kT_e$ may be obtained from the slope of the characteristic curve at V = 0.

$$\frac{dI}{dV} = \frac{di_{e1}}{dV} = -\frac{di_{e2}}{dV} \qquad (1.3)$$

Substituting 1.1 and 1.2 into 1.3 yields

$$A_1 j_r e^{-eV_1/kT_e} \frac{e}{KT_e} \frac{dV_1}{dV} + A_2 j_r e^{-eV_2/kT_e} \frac{e}{kT_e} \frac{dV_2}{dV} = 0 \qquad (1.4)$$

$$V = V_1 - V_2 \qquad (1.5)$$

$$1 = \frac{dV_1}{dV} - \frac{dV_2}{dV} \qquad (1.6)$$

Therefore 1.4 becomes

$$A_1 e^{-eV/kT_e} \frac{dV_1}{dV} + A_2 e^{-eV/kT_e}\left(\frac{dV_1}{dV} - 1\right) = 0 \qquad (1.7)$$

$$\left.\frac{dV_1}{dV}\right]_{V=0} = \frac{A_2}{A_1 + A_2} \qquad (1.8)$$

The first of Eq. (1.3) becomes, at V = 0.

$$\left.\frac{dI}{dV}\right]_{V=0} = \frac{A_1 A_2}{A_1 + A_2} j_r \frac{e}{KT_e} e^{-eV_f/KT_e} \qquad (1.9)$$

since

$$j_+ = j_r e^{eV_+/KT_e}$$

we have

$$\left.\frac{dI}{dV}\right]_{V=0} = \frac{e}{KT_e} \frac{A_1 A_2}{A_1 + A_2} \qquad (2.0)$$

finally since $i_{i1} = A_1 j_+$ and $i_{i2} = A_2 j_+$ we get

$$\left.\frac{dI}{dV}\right]_{V=0} = \frac{e}{KT_e} \frac{i_{i1} \cdot i_{i2}}{i_{i1} + i_{i2}} \qquad (2.1)$$

Therefore

$$T_e = \frac{e}{K} R_o \frac{i_{i1} \cdot i_{i2}}{i_{i1} + i_{i2}} \quad (2.2)$$

where

$$R_o = \left.\frac{dV}{dI}\right]_{V=0} \quad (2.3)$$

Since this calculation depends on the equivalent resistance between the probes evaluated at V = 0 it is called the "Equivalent Resistance Method", and R is called the "Equivalent Resistance".

1.5 Research Objectives

A distinct disadvantage in measuring parameters of a glow discharge is that a change in the dc current will usually cause a change in the electron temperature, electron density and the electric field. The experimental set up using an rf discharge superimposed on a dc discharge was chosen so that one of these parameters could be held constant while measuring the dependencies of the other parameters separately.

The objectives of this research project are threefold as explained below. In general the three areas are:

(1) Study of rf discharges

(2) Study of wavelength and electric field of a dc discharge perturbed by an rf signal

(3) Study of electron temperature in a dc discharge perturbed by an rf signal.

### 1.5.1 Standing Striation Phenomena in rf Discharges

Nakata, Takenaka and Masutani [13] made preliminary, but very interesting, observations concerning the possibilities of stationary striations being explained in terms of standing wave phenomena. It was decided to compare and evaluate the results of their experiment with the results of this experiment which utilizes a more powerful rf signal and larger discharge tubes. A more detailed discussion of their paper will be presented later in this thesis.

### 1.5.2 Wavelength and Electric Field

Novak [14] carried out measurements of striation wavelength in helium and neon in a region where self excited striations do not occur. He applied a high voltage pulse to the electrode of a homogeneous discharge. This produced a wave of stratification. The measurement of wavelength was made by means of photomultiplier-oscilloscope circuitry. Measurement of the electric field was accomplished with the use of two probes. He assumed that the electrostatic charges of the two probes were the same and hence canceled when measuring the potential drop in the positive column. The experiments were carried out in this region to cut out external effects such as distortions due to non standard effects or due to back coupling of the external circuit.

In evaluating the results of this experiment Novak found that the wavelength is a function of the electric field. The dependence was found to be hyperbolic. The relationship is $E\lambda = \phi$ where $\phi$ is a constant

independent of current, pressure, or tube diameter. $\phi$ has the significance of potential fall between corresponding points of neighboring striations. It is dependent only on the type of gas and the type of striation. Novak concluded that the wavelength, a basic parameter of the discharge, is uniquely determined by the longitudinal electric field, implying that the electric field is the basic defining parameter for the creation of moving striations in a glow discharge. It was decided to evaluate this relationship under the conditions whereby the dc glow discharge is perturbed by an rf signal. It is felt that although external distortions are possible, under these conditions the distortions, if they exist at all, would not be of sufficient magnitude to disrupt this relationship.

1.5.3 Electron Temperature

Pekarek and Krejci [15] using a simplifed set of equations conclude that one condition that is essential for the appearance of moving striations after an external perturbation is that the rate of production of ion pairs is dependent on the electron temperature and hence on the intensity of the local electric field [15] . This implies that the electric field is proportional to the electron temperature for a dc discharge.

It was decided in the course of this experiment to evaluate this relationship.

## 2. Previous Work

### 2.1 Moving Striations in Glow Discharges

In the early 1930's W. Pupp [19] published a series of papers concerning his experiments with moving striations. Pupp used photomultiplier tubes and oscilloscopes to show that there exists a critical current inversely proportional to the pressure, above which there are no moving striations. Pupp also showed that moving striations are associated with potential fluctuations and changes in the electron temperature and density. Pupp used two movable photo-multiplier tubes in conjunction with an oscilloscope to measure wavelength, which is the method used in this experiment. Pupp concluded that anode oscillations and moving striations were independent and that moving striations were produced in the positive column. In the intervening years several theories were put forth which disagreed with this hypothesis, notably those of Zaitsev [20] who asserted moving striations are a result of oscillations at the anode, Gordeev [41] who postulated that positive moving striations are due to electron oscillations in the anode fall region, and Loeb [21] who suggested the cathode as the orgin of moving striations. Others who disagreed with Pupp's conclusion were, Takamine, Suga and Yanagihara [42] and Coulter [43] who concluded that moving striations were due to anode spots stripping off the anode. In 1961 however, Cooper [22] in a series of experiments on the orgin of moving striations showed agreement with Pupp's conclusion. The results of

these experiments are:

(a) The striation frequency, velocity and wavelength all change discontinuously at a change in tube diameter.

(b) Visible spot oscillations are accompanied by oscillations in discharge potential, and exist unchanged above the critical current for disappearance of moving striations.

(c) Anode oscillations and anode spots may be suppressed by operation of an auxiliary discharge to the anode.

(d) The striation frequency synchronizes to an applied oscillation at the anode, provided the applied frequency is close to a small integral multiple of the natural striation frequency.

(e) A striation system can be maintained in a vessel separated from the electrodes by narrow tubes operated above the local critical currents for moving striations. No oscillations were detected in the isolating regions either photoelectrically or with electrostatic probes.

From these results Cooper drew two conclusions:

(1) Anode oscillations and moving striations are independent phenomena.

(2) Moving striations result from a local instability in the positive column and not from an external disturbance.

In 1955, Oleson and Watanabe [24] produced a theoretical derivation that established the possibility of ion density waves and electron waves in the positive column of a glow discharge. The authors were careful not to directly associate these waves with moving striations.

In 1957 Robertson [25] presented a theory which involved a new approach to the problem. His theory is based on a theoretical description of the processes in a plasma. He started from the continuity equations for electrons, ions

and metastable atoms. Then by making suitable assumptions concerning mobility and loss mechanisms and assuming a plane wave solution equations were obtained which could be used to characterize the propagation of striations. This was the first theoretical model to take metastable atoms into account. Although containing some weaknesses the theory indicates the possibility of an instability which can originate in the positive column and could lead to moving striations in metastable dependent plasmas.

The most notable theory in the field of moving striations to date is Pekarek's [26] theory of the wave of stratification. Pekarek applied an impulse to a homogeneous plasma and observed a fast and slow wave packet traveling to the anode. From this he developed the wave of stratification concept, from which he concluded that the process of gradual stratification of the plasma leads to the appearance of moving striations. He claims that moving striations are connected with an increase of electron temperature at the cathode end of the column. This leads to a local increase in ionization. The electrons produced from the point of production move more rapidly than the ions, leaving a positive charge in the area of increased ionization. This positive charge induces an electric field which slows up the electrons moving toward the anode which in turn leads to a region of reduced ionization. An electric field is again established leading to an increase in electron temperature and thus an increase in ionization. This

process repeats itself continually, leading to stratification of the positive column. These alternate regions of positive and negative space charge Pekarek associated with striations. He associated the wave of stratification with the propagation of polarization of the plasma caused by the alternate space charge. In his papers he has presented evidence to show that the production of moving striations is influenced by:

(1) The tendency of the plasma to stratification.

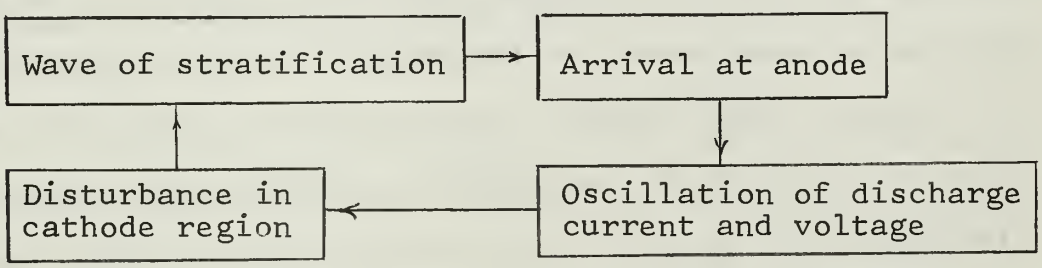
(2) The length of the positive column.

(3) Processes in the regions of the electrodes.

(4) The external circuit.

(5) The presence of metastable atoms.

Pekarek further proposed that the wave of stratification repeat through a feedback loop;




In recent years Pekarek and Krejci [15] have worked on developing a theory on striation processes. They have developed an integro-differential equation that they propose as a basic equation. Solutions to the equation have been found to be quite consistent with macroscopic and experimental observations.

In 1963 Kenjo and Hatta [30] showed that the striation wavelength in a smoothly tapered tube is proportional to

$r^n$ where r is the tube radius and n varies from 1.5 to 2.0. They indicated that it may be possible to explain this in terms of electron temperature and ionization phenomena.

2.2 rf Discharges

Although the rf discharge has been known for some years little research was conducted until 1920. The first theory to explain the electrodeless ring discharge was advanced by J. J. Thompson in 1930. This theory has already been discussed.

In 1926 Richards [31] showed that the distance between two striations was equal to the distance traveled by the positive ions in the tube during a half period of the discharge. Banjeri and Ganguli [33] drew the conclusion from their experiments that due to the oscillatory motion of the electrons in an rf discharge, the half cycle of alternation must be at least equal to the period between two successive collisions. They further implied that the main influence of an ac field is to concentrate positive ions close to the electrodes and to drift out electrons due to their motion.

Kojima and Takayama [35] using the configuration shown in Fig. 17d studied hf discharges in a pressure range of 1-10 torr with a frequency of 200 MHz. They used the double probe method to measure electron temperatures and densities and confirmed that the electron distribution under these conditions is maxwellian.

Jones and Morgan [36] experimented with hf discharges in air and hydrogen and found that geometrically similar

systems break down at the same potential provided ap and f/p are invariant, where a is a linear dimension. They showed also that the secondary ionization processes do not play as important a part in this type of discharge as they do in the case of a static discharge.

In 1950 Brown et al [44] in a study of rf discharges under the influence of transverse magnetic fields showed that there are two main effects caused by the magnetic field. The first is the presence of an energy resonance condition and the second is a reduction of diffusion. These effects were shown experimentally and theoretically explained using the Boltzmann theory.

Vlaardingerbroek [45] showed that at low frequencies the increase in the ac breakdown field that occurs with an increase in frequency is caused by the slow build up of the discharge.

In 1952 Brown [46] determined that the only production phenomenon controlling the breakdown is the primary ionization from electron motion. This agrees with the findings of Jones and Morgan [36]. He also showed that the energy absorbed due to collision is proportional to the square of the electric field.

Eckert [47] in 1962 developed a diffusion theory for the electrodeless ring discharge for which there is considerable experimental agreement. It is a modification of the theory proposed by J. J. Thompson in 1930.

The following year Eckert [48] theoretically developed a simple method for measuring the time dependence of the average electron density during the inductive formation of an hf discharge. In this derivation he assumed the only competing processes to be the electron production and diffusion.

In 1965 Beerwald [50] measured ionization rates in rf discharges and showed that when the electric field is applied the electron density grows exponentially with time.

Chandrakar and Von Engel [51] using a standard ring discharge showed that a faint discharge starts when the rf current in the ring exceeds a critical value. The discharge develops as the current is raised. The development occurs in two stages, one associated with the axial component of the electric field and the other with the azimuthal component of the electric field.

The experiments of Nakata, Takenaka and Masutani [13] will be discussed in some detail since one of the objectives of this thesis is to evaluate their findings under the conditions of this experiment. Nakata et.al. [13] made a study of stationary striations in an hf discharge in argon over a pressure range of .07 to 8 torr, in tubes of diameter from 5.8 mm to 18 mm. They found that the wavelength is proportional to the electrode distance within a limited range of the wavelength, and to the radius. The number of striations existing between the electrodes is always integral. They stated that the wavelength increased as the hf power

increased; however, they used input dc current to the hf oscillator as an indication of the power. The validity of this assumption is questionable. They found no influence of the frequency on the wavelength over the range 5 MHz to 53 MHz. They also determined that the wavelength decreases with an increase in pressure until a certain value is reached. They observed that increasing pressure causes a decrease in electron temperature but does not affect the density. A power increase, using input dc current as a power indicator, leads to an increase in electron density but has no effect on the electron temperature. These last two observations are most interesting but imply a need for further research in this area. Nakata, Takenaka and Matsutani drew three conclusions from their experiments. They were careful to point out that these are possible explanations, and indicated that further analytical analysis is needed. The conclusions are:

(1) Stationary striations may have the nature of standing waves.

(2) A striation may require the appropriate ratio of the striation length to the radius in order to exhibit the stationary nature.

(3) Movement of striations is possibly caused by the dc field or the dc current.

## 3. Experimental Equipment and Procedures

### 3.1 Vacuum System

A schematic diagram of the vacuum system is shown in Fig. 9. The system is constructed of glass and mounted on a rack and table. It consists of a three stage oil diffusion pump backed by a mechanical fore pump which evacuated the system and the discharge tubes. Two traps cooled with liquid nitrogen were used, one between the manifold and the discharge tubes, and one between the manifold and the pump. One high vacuum bakeable valve was situated so that the discharge tube could be isolated from the rest of the system. All glass stopcocks were vacuum type lubricated with type N apiezon grease. In the bakeout process all glass work was wrapped with heating tapes and the system was baked for periods in excess of six hours, at temperatures of 200°-250°C. During the bakeout process the ionization guage was outgassed in accordance with manufacturers instructions. The cathode filament was heated with a current of 7.5 amperes for periods of up to twenty minutes. Dissolved gases and impurities in the surface of the anode were driven off by using a Scientific Electric Co. induction heater, to heat the metal to a bright red-orange color. It was found that baking of the traps helped to achieve a lower base pressure. Final purification was achieved by filling the discharge tube with neon at about 10 torr and running a discharge. While the discharge was running, the tube was pumped down very slowly. This procedure was repeated several times. The base pressure was measured with a Veeco Ionization guage, type RG 31 A with an RG 75 sensing tube for high vacuum measurements. Base pressure in these

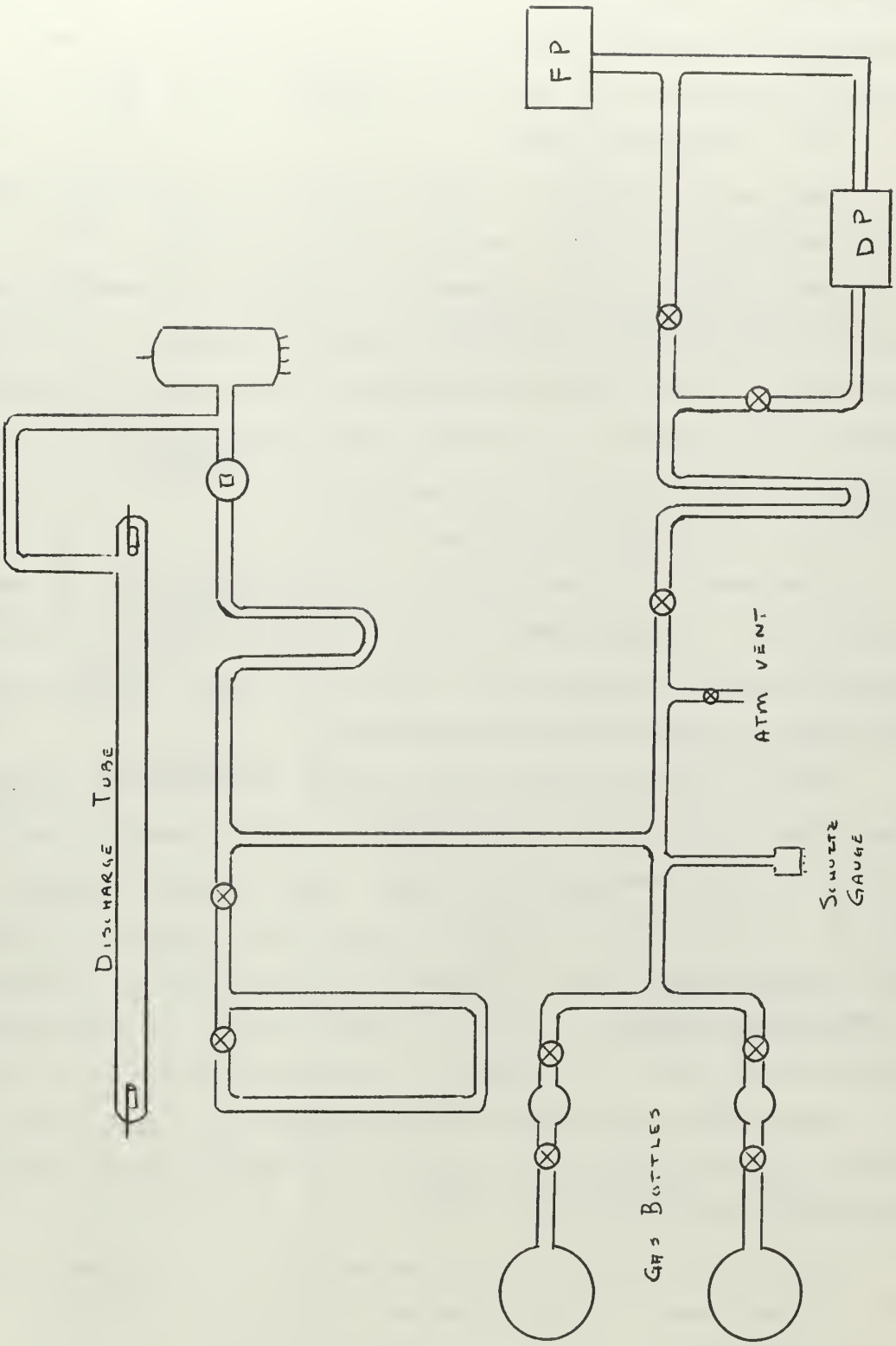



Fig. 9. Vacuum system.

experiments ranged from $7.5X10^{-8}$ torr to $2X10^{-7}$ torr. Gas pressure in the tube after filling was measured on an octoil-s manometer (1 cm of oil equals .762 mm Hg).

3.2 Discharge Tubes

Two basic discharge tubes were used with several probe configurations as can be seen in Fig. 10 and 11. The cathodes consist of a cylinder of tantalum surrounding an oxide coated spiral strip. The anodes consisted of tantalum cylinders. Both tubes were operated hot cathode at currents from 0 to 1 ampere. All probes were constructed of 8 mil tungsten wire in glass capillaries.

3.3 Electronic Circuits

A schematic of the general circuits used can be seen in Fig. 12. A Kepco Model 770B, voltage regulated dc power supply having a range of 0 - 3 amp, 600 volt maximum output was used for the main voltage supply.

Three resistor banks were needed in series to handle the range of currents investigated. For currents less than 120 ma a 16000 ohm bank was used. For currents between 120 ma and 1200 ma two 1000 ohm resistors placed in series were used. The cathode filament was heated with a laboratory constructed, voltage regulated power supply with current capacity of zero to 15 amps at voltages of zero to 30 volts.

The power supply for the photomultiplier tubes was a locally constructed supply especially designed for photomultiplier applications.

A Houston Omnigraphic Corporation x - y recorder model HR - 96 was used to obtain probe characteristic curves. The wiring diagram for the x - y recorder circuitry for the single probe set up is shown in Fig. 13. This same circuit was utilized in the double probe situation by removing the ground leads and connecting them to probe number two.

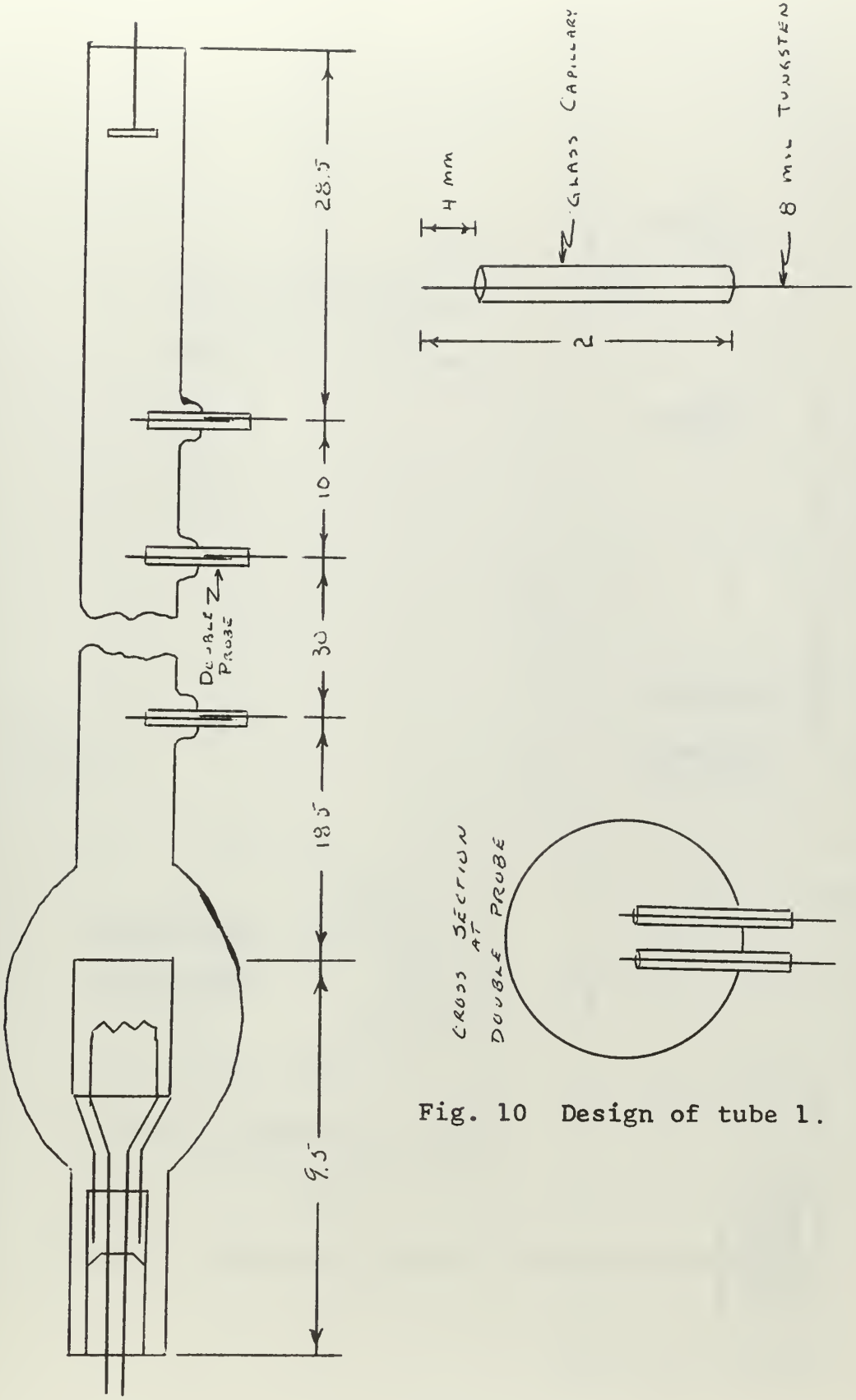



Fig. 10 Design of tube 1.

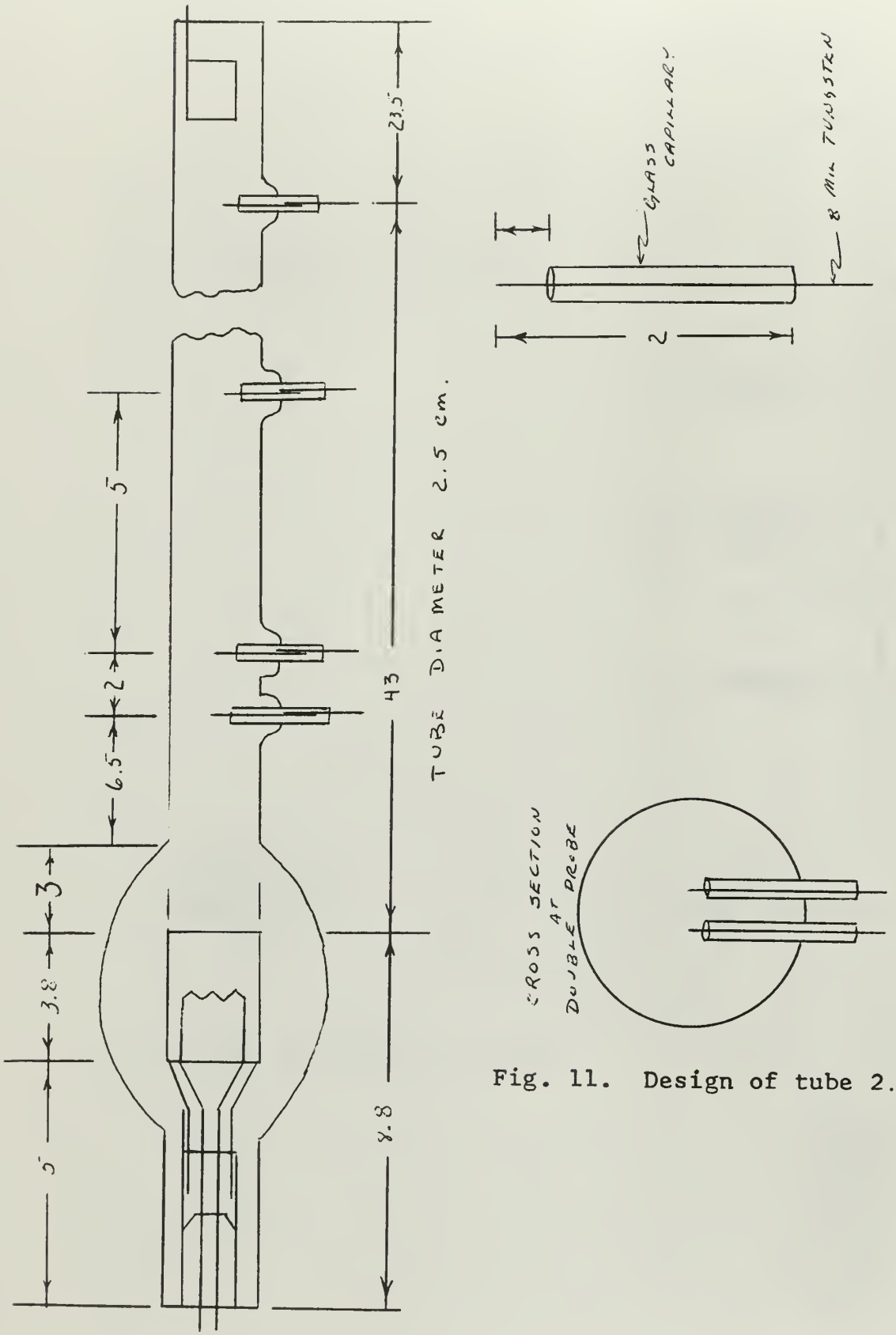



Fig. 11. Design of tube 2.

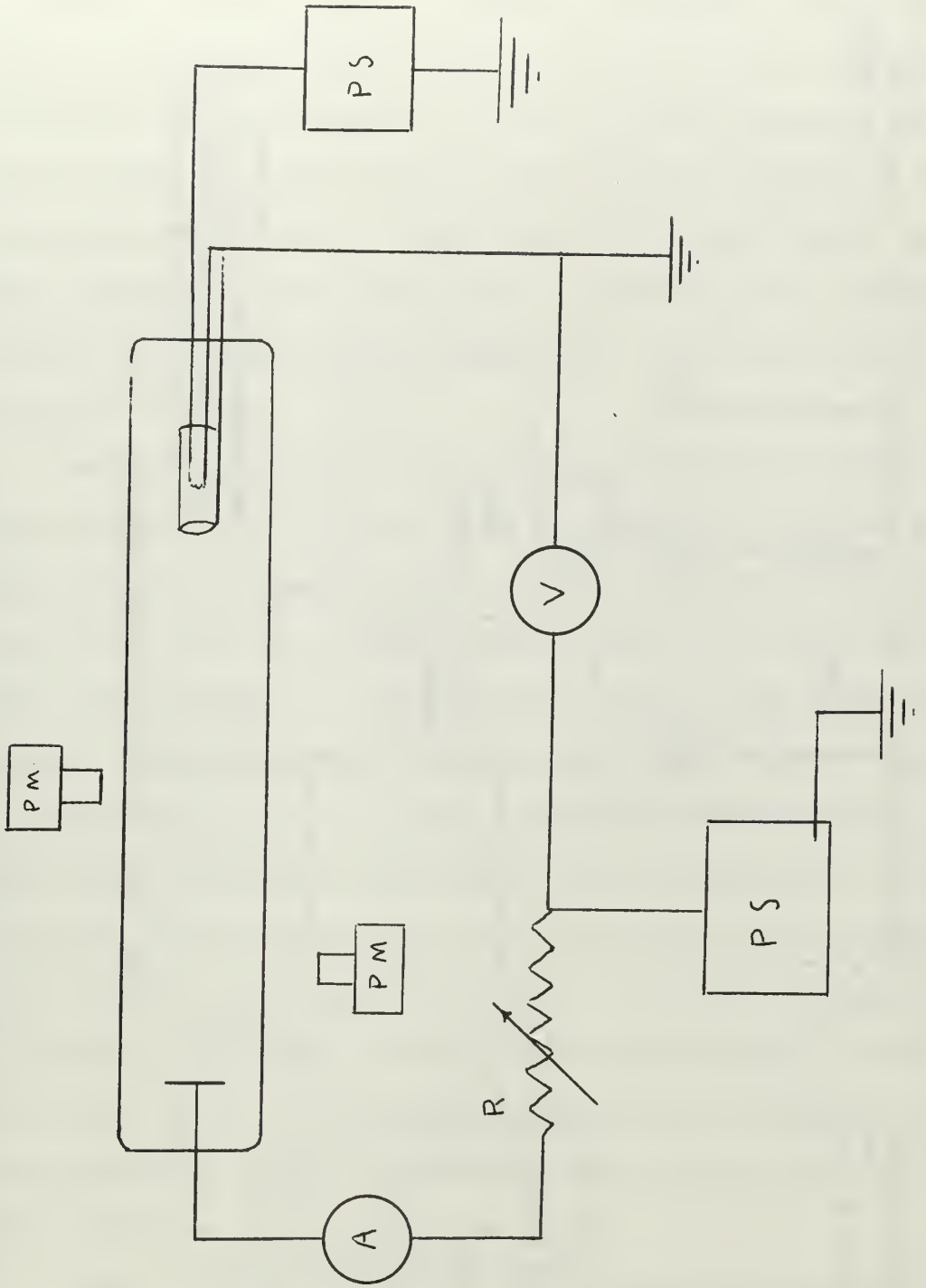



Fig. 12. Electronic circuit for main discharge.

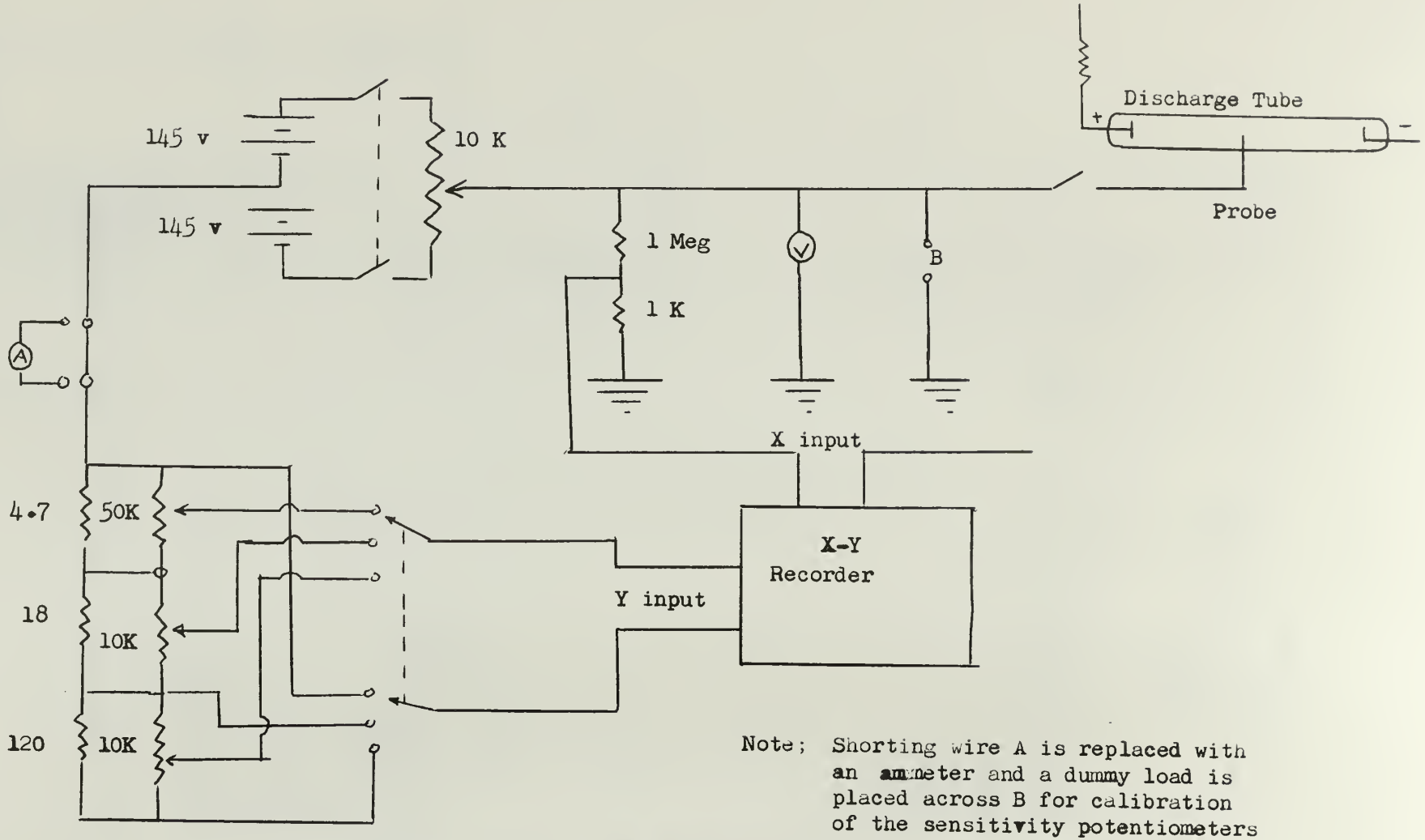



Fig. 13. X - Y recorder circuit.

### 3.4 TCS-9 Radio Transmitter

The rf signal used to run the discharge in these experiments was obtained with a TCS-9 transmitter manufactured by Collins Radio company. It has a 3 band frequency range from 1.5 MHz to 12 MHz with a power output from 24 to 40 watts continuous wave. A watt meter was unavailable but the power transmitted was evaluated by observing the antenna current which was read in rf amperes. This gave a relative reading of power.

Many sizes and types of antenna leads were tested for best performance. It was found that plain insulation was unsatisfactory because it was greatly affected by outside conditions such as moving your hand near it. This caused great fluctuations in rf "antenna" current. In addition it was felt that radiation from the wire could effect other instrumentation. It was then decided to use shielded leads. Many sizes of coaxial cable were used including one constructed in the laboratory with an air gap greater than one inch. Most were unsatisfactory due to arcing through the dielectric. The most suitable lead was RG-62A/U and was discovered mainly by accident. It gave good results without the problem of arcing and in addition was not effected by such things as hands moving near it.

Power to the transmitter was supplied by a rectifier power unit, type COL 20218.

An antenna loading coil, type CMX47205 was sometimes used in series with the antenna to increase the power output

by matching to the load. This allowed a greater range of operations. It was generally helpful near the ends of a frequency range.

3.5 Measuring Equipment

The principal measuring device was a Tektronix dual beam oscilloscope, model 555A, with type CA preamplifiers. With this oscilloscope output from both photomultiplier tubes could be displayed simultaneously and relative movement shown.

3.6 Rotating Mirror

The rotating mirror used in these experiments is the one built by Cooper [6]. It consists of a stainless steel block, machined and fitted with a pressed fit axle. One surface was polished to a smoothness of one quarter of a wavelength of sodium D light, and coated with an evaporated aluminum layer, which was then covered with a dielectric film to reduce pitting. The mirror has a continuous range of speeds from 0 to 9250 revolutions per minute, with a constant motor speed. The entire assembly is balanced for rotational speeds up to 10,000 revolutions per minute.

3.7 Wavelength Measurements

Two photomultiplier tubes were used to measure the wavelength of the moving striations. One was stationary while the other was mounted on a scaled track. Both photomultiplier outputs were displayed on the oscilloscope. Both traces were triggered by the signal from the stationary photomultiplier tube. As the photomultiplier on the track

was moved parallel to the discharge the traces would go in and out of phase with each other. The distance that the photomultiplier tube moved when the oscilloscope trace went through one phase change was the wavelength. Figure 14 shows the circuitry involved in these measurements.

3.8 Frequency Measurements

The frequency of the moving striations was measured with a Hewlett Packard electronic counter model 521A. The signal from the photomultiplier tube was amplified with a Hewlett Packard decade amplifier model 450A and then fed into the electronic counter. This system allowed more accurate and faster measurements of the frequency. In all cases the wavelength was measured ten times and the statistical average computed.

3.9 Velocity Measurements

The velocity of the moving striations was determined from the wavelength and frequency by the formula:

$$v_p = \lambda_p \cdot \nu_p$$

where $\lambda_p$ is the phase wavelength and $\nu_p$ is the frequency.

3.10 Electric Field Measurements

The longitudinal electric field was determined by measuring the difference in potential between two probes and dividing by the distance between them, utilizing the relation

$$E = - \frac{dV}{dx}$$

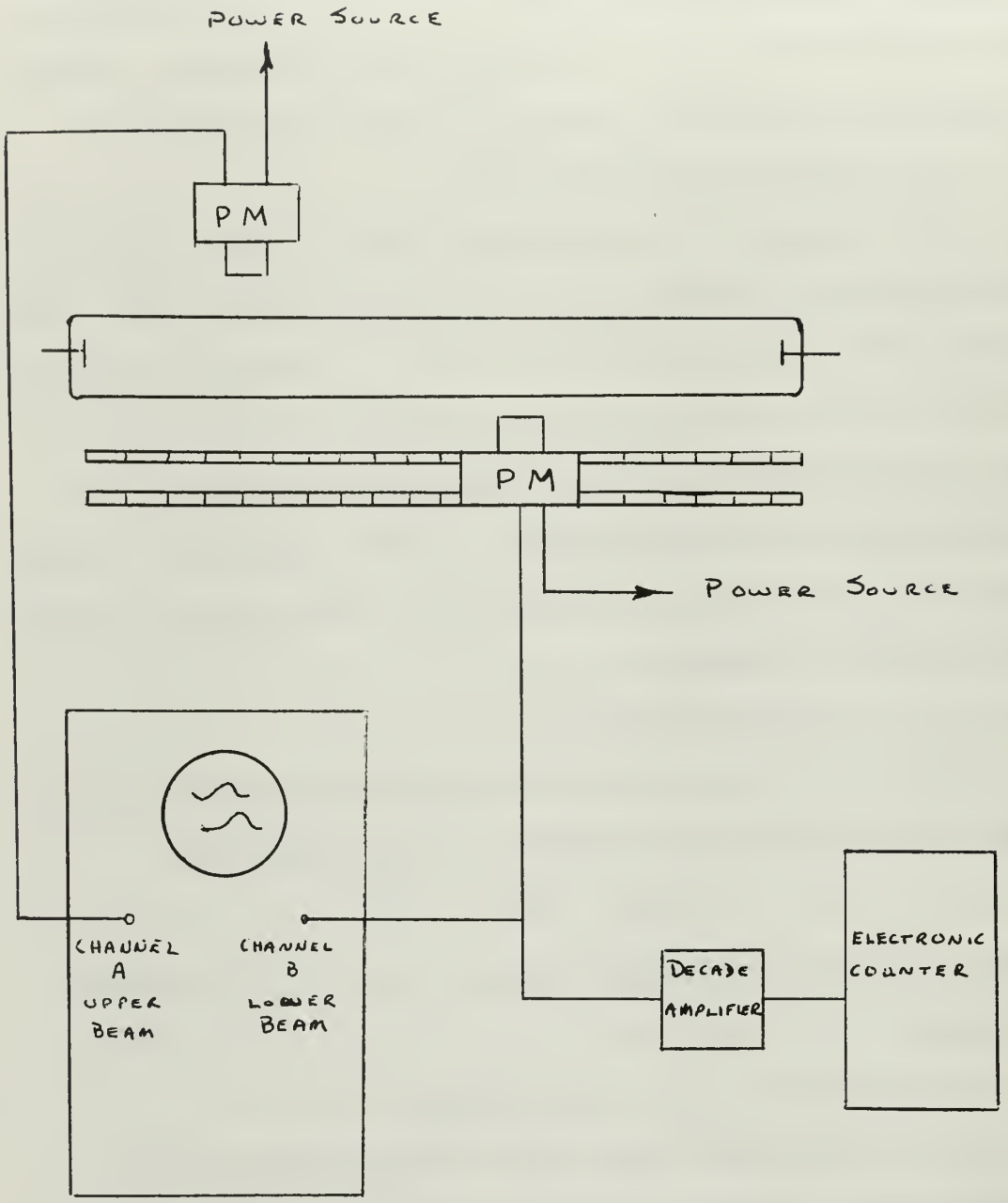



Fig. 14. Circuit diagram for wavelength and frequency measurements.

A Keithley model 600 A, battery powered electrometer with an input impedance of $10^{12}$ ohms was used to measure the potential between the probes in order that the current drawn would not effect the plasma, and to avoid grounding problems.

3.11 Sliding Wire Photographs

In this procedure a photomultiplier tube is moved along the length of the positive column. The output from the photomultiplier is used to intensity modulate the oscilloscope beam. At the same time the time base on the X axis is triggered by another photomultiplier tube observing the light intensity changes from a stationary point in the positive column. This results in a display of stationary horizontal dashes on the oscilloscope, each dash representing one striation. There is a slide wire contact carried by the photomultiplier which gives a voltage signal proportional to the distance the photomultiplier is from the head of the positive column. This signal is fed into the y input of the oscilloscope. When the photomultiplier tube is moved along the positive column the oscilloscope trace moves down the screen. Thus it is possible to study the motion of the striations as a function of time and space. Figure 15 shows the sliding wire circuitry and Fig. 16 shows a time delayed photograph of this phenomenon in a dc discharge. Originally it was hoped that this system could be used to study the motion of the striations as functions of time and space in rf discharges, dc discharges and dc

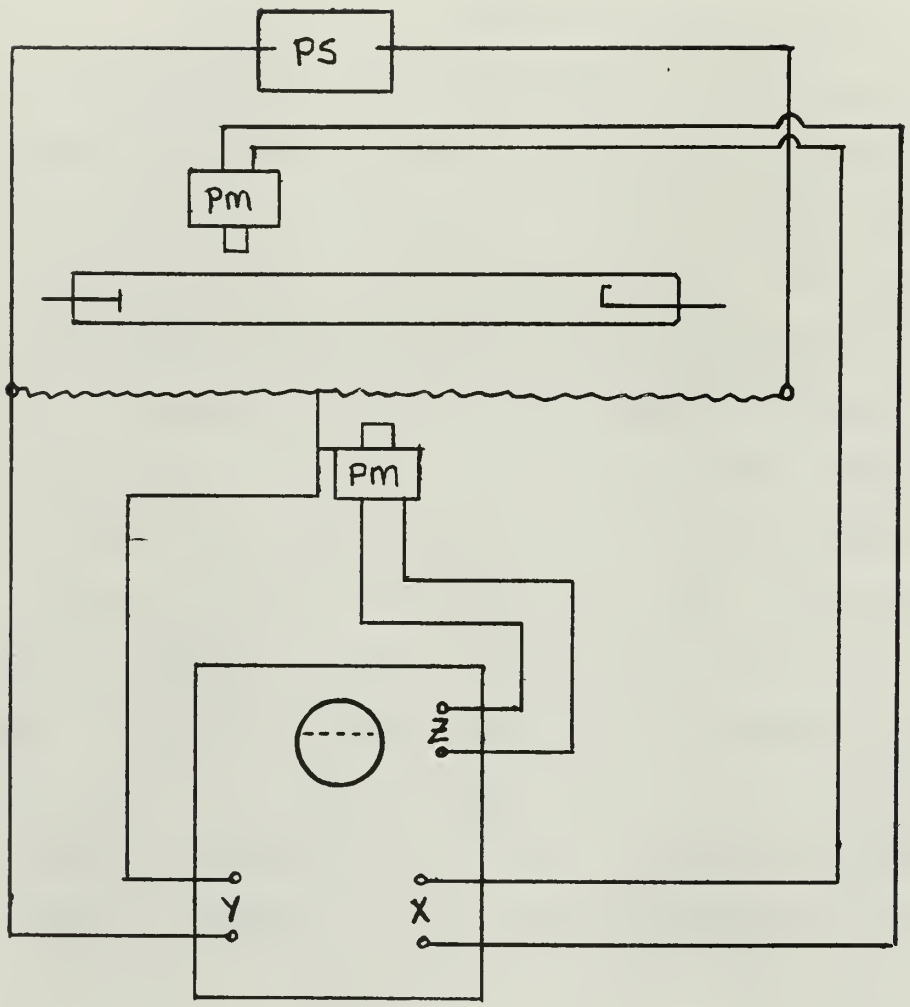



Fig. 15. Sliding wire circuit diagram.

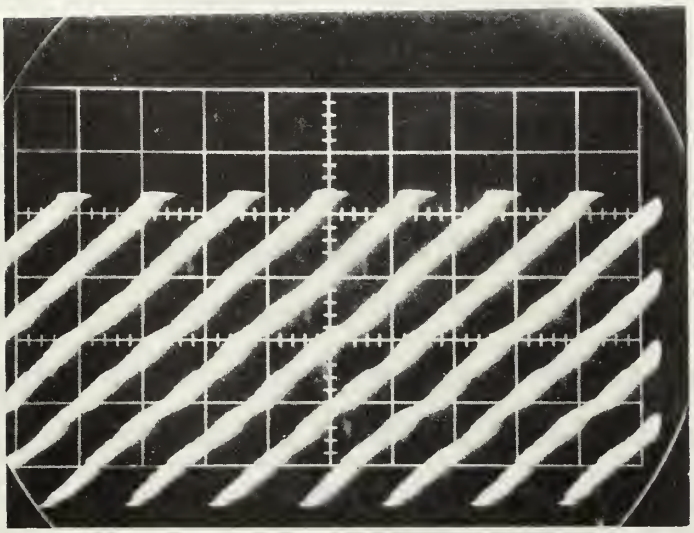


Fig. 16. Sliding wire Photograph

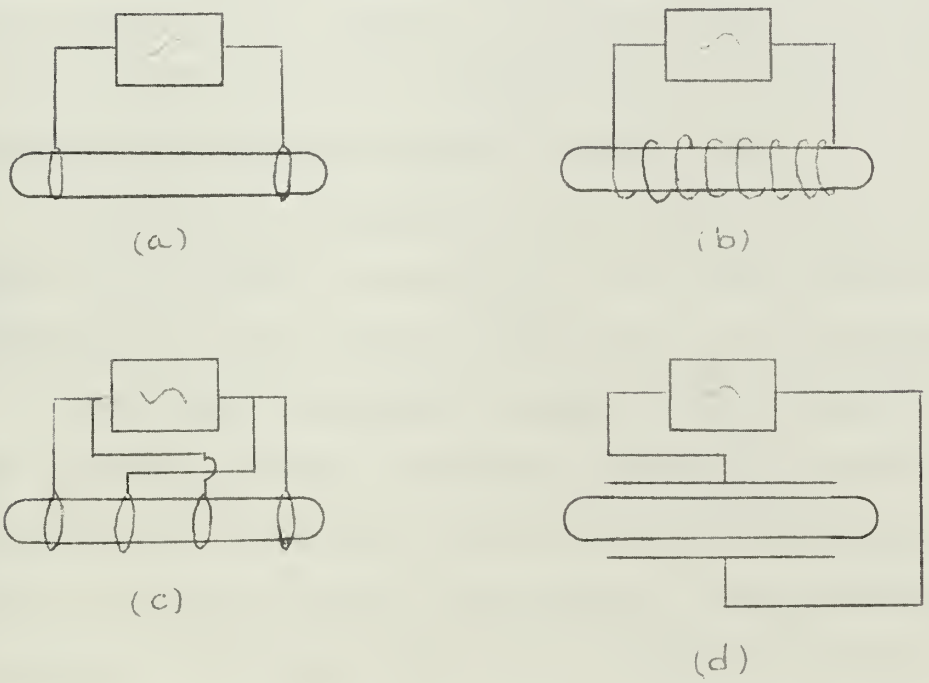



Fig. 17. Various electrode configurations for rf discharges.

discharges perturbed by an rf signal. This turned out to be unsuccessful because the rf discharge showed no moving striations and the perturbed dc discharge had the horizontal dashes replaced by vertical lines which completely obliterate the picture when the sliding wire contact is moved along the length of the tube. For this reason the rotating mirror was used to study the movements in rf discharges.

## 4. Experimental Work and Results

The experimental work was divided into five major areas which for the most part are interrelated. The five areas will be discussed in the order in which they evolved in these experiments.

### 4.1 rf Discharges

rf power was delivered with the antenna lead of the TCS-9 transmitter to electrodes consisting of #12 copper wire wrapped around the discharge tube. In general it was found that rf discharges could be obtained in any of the configurations shown in Fig. 17. The configuration in Fig. 17(a) was chosen because it gave greater light intensity and higher antenna currents, ie, more power out. There appears to be a limit to the amount of power that can be fed into the plasma in this manner. A plot of the rf current versus the transmitter frequency shows that the current increases to a maximum and then falls. See Fig. 18.

A dark space appears on both sides of the electrode when the discharge is running. It is very similar in appearance to the cathode dark space in a dc discharge.

Stationary striations depend on the pressure which has two threshold values. Standing striations are not present below certain pressures and there is also an upper pressure limit at which they are not visible. As the pressure approaches the upper limit the standing striations get less and less distinct. The standing striations are not subject to a size change due to the pressure. This is not contrary

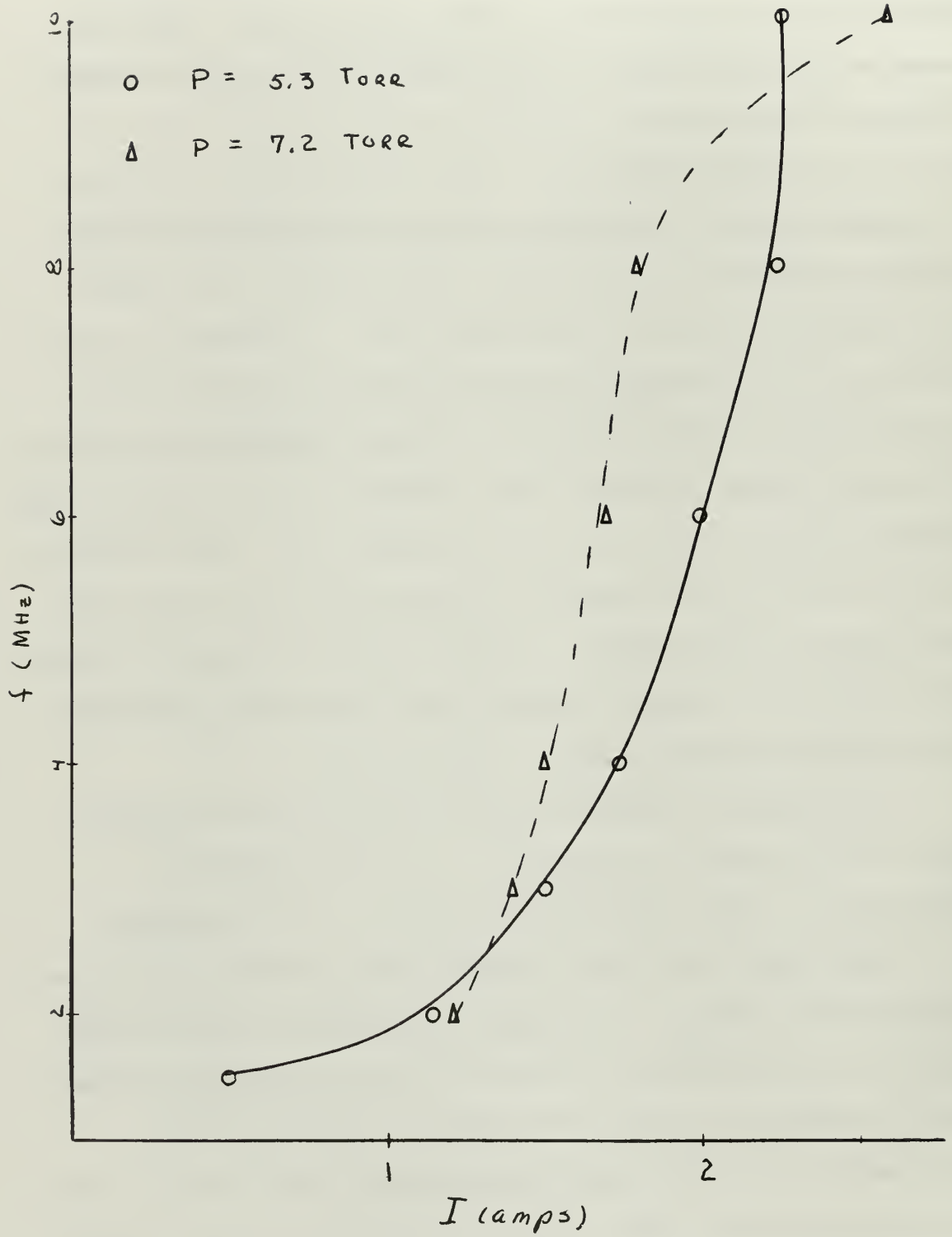



Fig. 18 Plot of frequency versus rf current.

to the findings of Nakata et. al. [13] in their experiments in smaller tubes. They found that the wavelength increased with pressure until a certain value was reached, at which it stopped. They did not indicate the pressure at which this occurred.

Standing striations always occur in an integral number. This number is dependent on the distance between the electrodes and on the wavelength. The relation between the inter-electrode distance and the number of standing striations is shown in Fig. 19. The wavelength is proportional to the inter-electrode distance but there is an upper and lower limit for it. The wavelength varies discontinuously everytime the electrode distance varies by an average wavelength. As a result the number of striations is always integral. Both characteristics have a hysteresis phenomenon in that when the electrode distance is increasing the upper limits become higher than when the electrode distance is decreasing.

When power is applied to the electrode a grounded electrode located further down the tube has an effect on the light intensity and the power fed into the discharge; however, it is a small effect. The visible glow in many cases extends past the grounded electrode. It appears that the power induced into the plasma travels as far as it can go, ie, until the power is dissipated by the medium.

The oscilloscope-photomultiplier and electronic counter circuit described early was used to determine if moving striations were present in the rf discharge. The oscilloscope

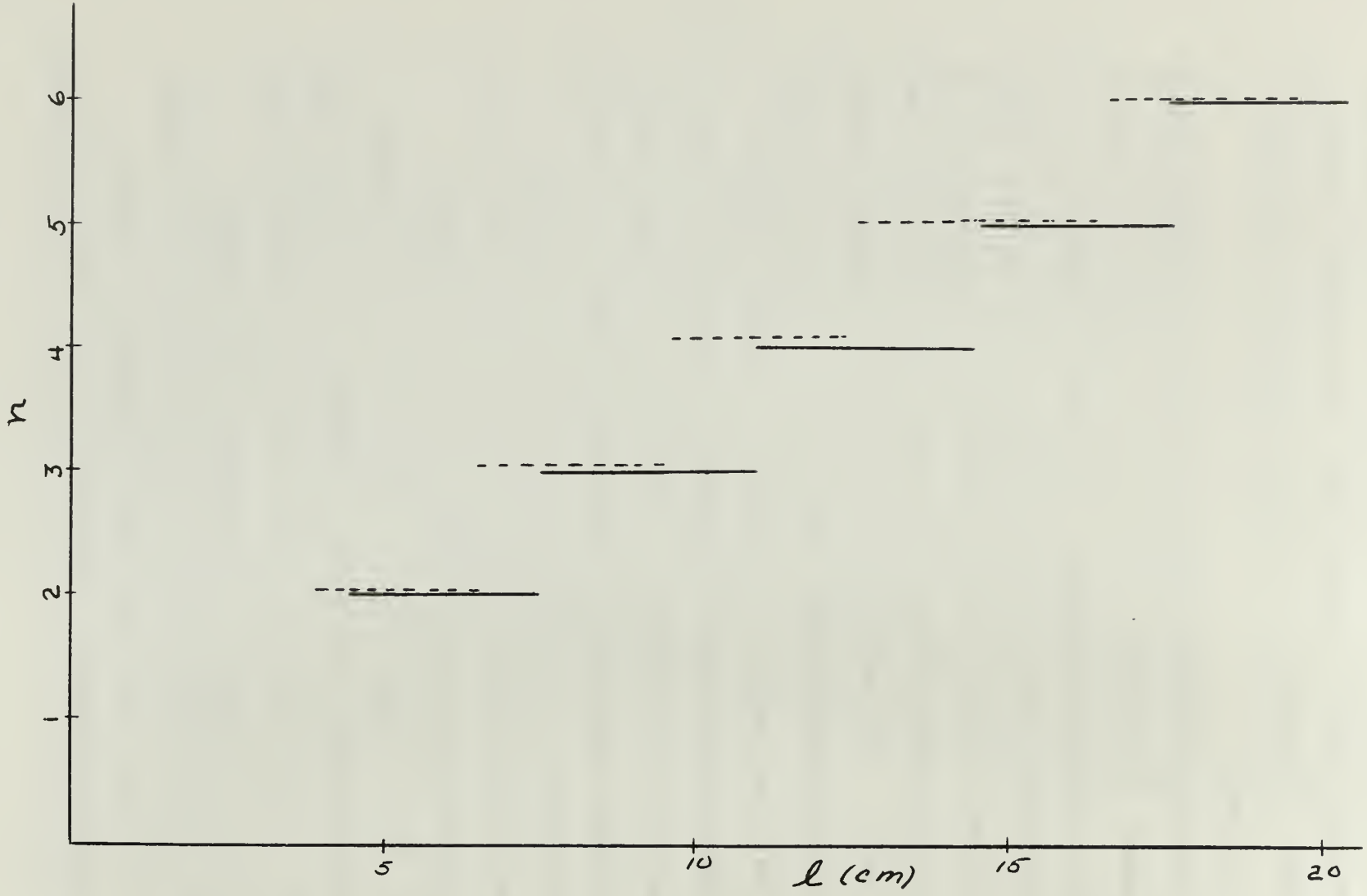



Fig. 19 Plot of striation number versus electrode distance.

showed that something of the appearance of a moving striation with a very small frequency (100-300) range exists in the rf discharge even while standing striations are distinctly seen by the naked eye. This disturbance appeared as an envelope containing the rf frequency. Figure 20 shows a double exposed photograph of this phenomenon. The large amplitude oscillation is an oscilloscope display of the disturbance with a horizontal sweep time of approximately 0.1 msec. The horizontal sweep time was changed for the second exposure to 0.1 microsec. This phenomenon occurred throughout the experiments. This variation of light intensity detected by the photomultiplier tube did not show itself in rotating mirror photographs as can be seen in Fig. 21. The fact that these two photographs do not correlate implies the existence of an asymmetry. This implication is strengthened by the fact that the intensity variation appears to move in one direction only. It moves toward the cathode. Attempts to determine the asymmetry causing this effect were unsuccessful. It was proven that the intensity variation picked up by the photomultiplier tube came from the discharge. The experiment was carried out in a dark room with no lights or other electrical circuits (except the oscilloscope). When the photomultiplier tube was shielded the light intensity did not appear on the oscilloscope. At this time the author is unable to explain this phenomenon.

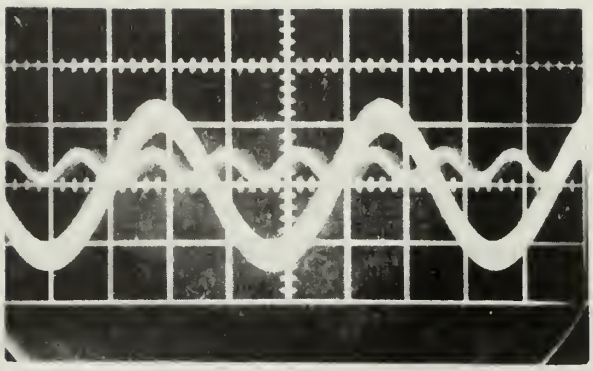


Fig.20. Photograph of moving and stationary striations.

Fig. 21. Rotating mirror photograph of moving and stationary striations.

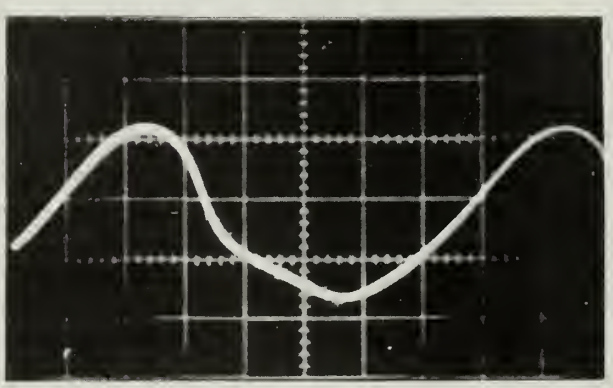


Fig. 22. Photograph of slowly moving stationary striations.

The stationary striations can be made to move very slowly as can be seen in Fig. 22 which shows the oscilloscope trace of moving striations in an rf discharge that are moving slowly enough to be seen by the naked eye. This movement can be caused by several factors, inappropriate electrode distance, electrical asymmetry, and geometrical asymmetry. It is very difficult to control these factors in making the striations move because a small perturbation of any one of these will start the striations moving with no control of direction or speed.

4.2 dc and rf Discharges in General

The general effect of superimposing an rf signal upon the dc discharge using the configuration of Fig. 17(a) was studied in preliminary investigations to get an idea of the changes occurring and their magnitude. The procedure was to start the dc discharge and then to apply the rf signal. It was found that the same effects occur if the rf is started first. When an rf signal is applied to the dc discharge there is a marked increase in the frequency of the moving striations and a decrease in the wavelength at dc currents below 100 ma. See Figs. 23 and 24. As the current increases this effect diminishes until at about one amp it is barely noticeable. As the frequency of the transmitter is increased the striation frequency increases to a maximum and then falls off as shown in Fig. 25. This occurs at a constant power level although the other discharge parameters are allowed to vary. The wavelength in general

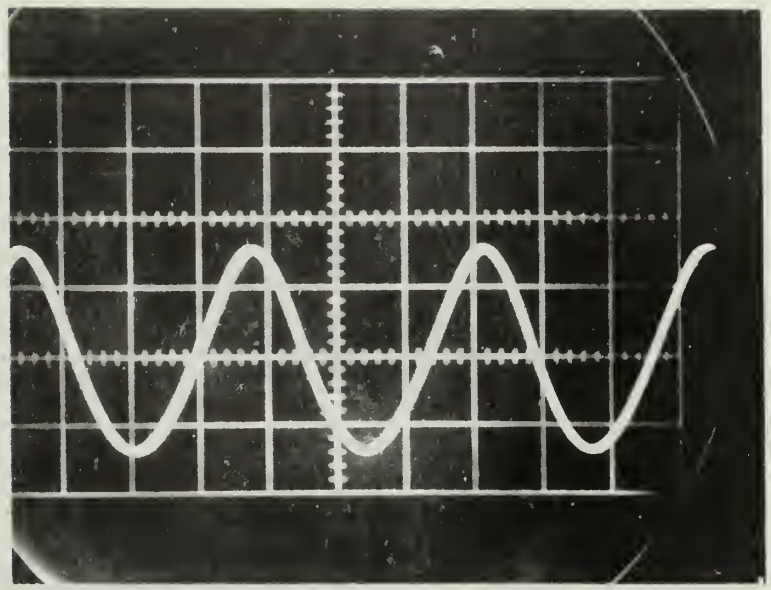


Fig. 23. Photograph of moving striations in a dc discharge

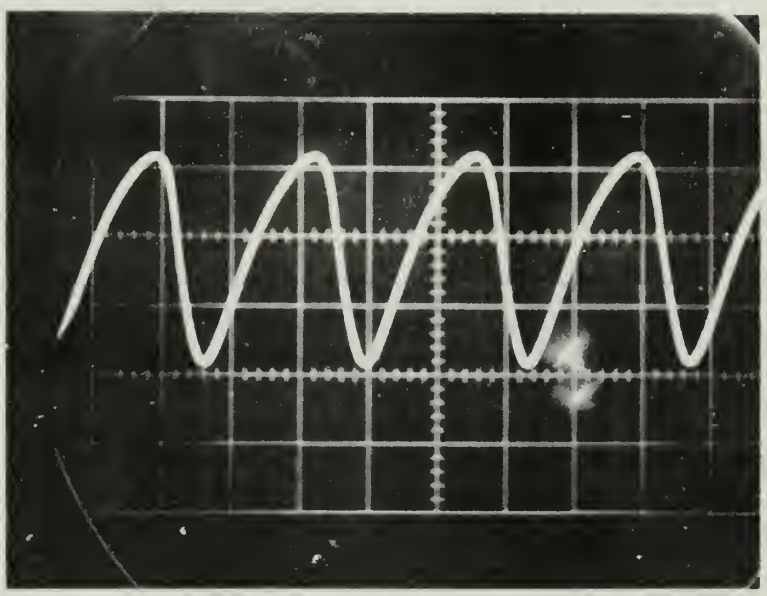


Fig. 24. Photograph of moving striations in a dc discharge perturbed by an rf signal

decreases to a minimum and then increases under this situation, (see Fig. 26). The electron temperatures during this period were obtained by the single probe method. In general imposition of the rf signal on the dc discharge caused a decrease in the average electron temperature and it continued to decrease as the frequency of the transmitter increased as shown in Fig. 27.

The electric field was not measured in this portion of the experiments, and therefore the effects of an rf signal on the electric field will be discussed in the next section.

4.3 Effect of rf perturbation When the Current is Held Constant

In the second set of experiments the current was held constant in an attempt to determine the influence of current as a parameter in the cause of the effects discussed in the previous section.

In these experiments the parameters of a dc discharge were measured for a range of selected currents. Then an rf signal was imposed on the dc discharge and the parameters were again measured using the same range of selected dc currents. The experiment was repeated over a range of rf frequencies from 1.5 MHz to 12 MHz. The pressure was then changed and the experiment repeated. This was done over a pressure range of 1-10 torr. This experiment was carried out in both tubes shown in Figs. 10 and 11. The parameters measured were the wavelength, frequency, velocity,

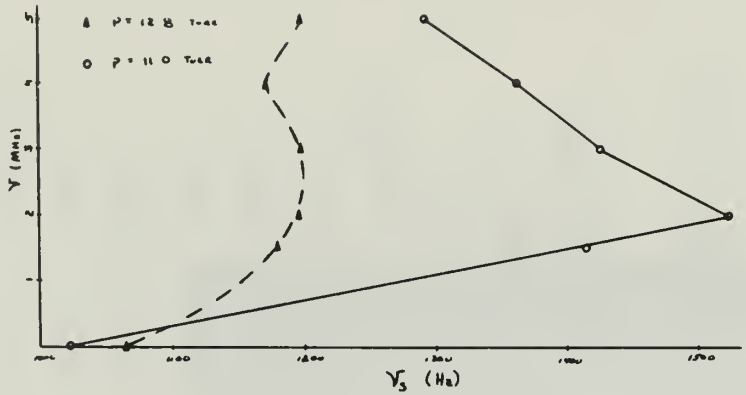


Fig. 25. Plot of rf frequency versus striation frequency

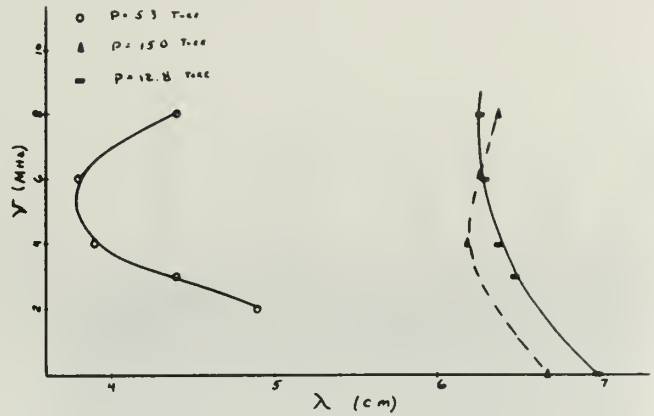


Fig. 26. Plot of striation wavelength versus rf frequency

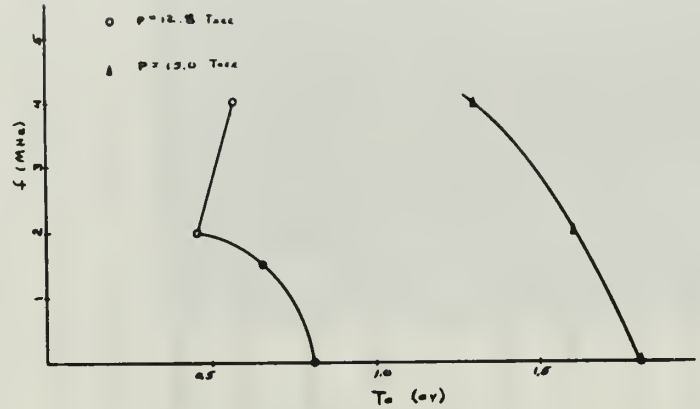


Fig. 27. Plot of electron temperature versus rf frequency

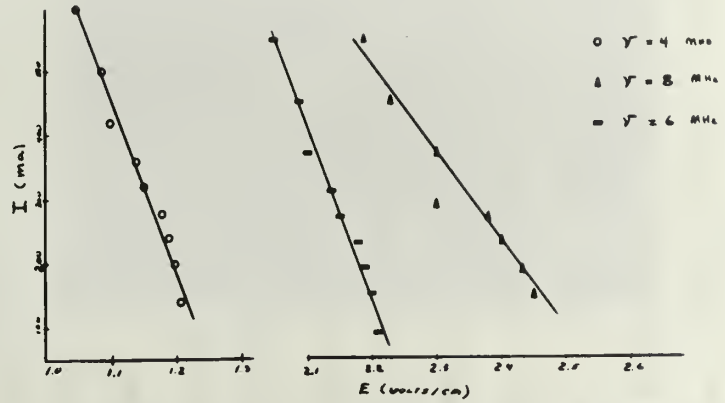


Fig. 28. Plot of dc current versus electric field

electric field and the electron temperature. An electrometer was used to measure the potiental difference across two probes, 10 cm apart in one tube and 20 cm apart in the other. The electric field was calculated from these data. In all cases the electric field decreased as the dc current increased regardless of the rf frequency, as shown in Fig. 28. This is to be expected. The relation of the wavelength and the electric field did not follow Novak's [14] hyperbolic relationship $E\lambda = \phi$. In some cases the relationship was linear (see Fig. 29) and sometimes there was no correlation at all. See Fig. 30. There were no runs in which this relationship was hyperbolic. On the contrary $\phi$ seemed to change with an increase in current as shown in Fig. 31. The effect of the rf frequency on the electric field is shown in Fig. 32. The electric field increases with increasing rf frequency until it reaches a maximum at about 3-4 MHz and then it decreases. This is unusual in view of the fact that the transmitter transmits more power in the upper frequency range. Applying the rf excitation to the positive column causes a decrease in dc current and an increase in dc voltage. The rf perturbation increases ionization in the positive column leading to an increase in dc current; however, the perturbation also causes an increase in losses to the walls which leads to a decrease in dc current. The losses to the walls predominate and the net effect is a decrease in dc current. The voltage is then lowered to raise the dc current back to its constant

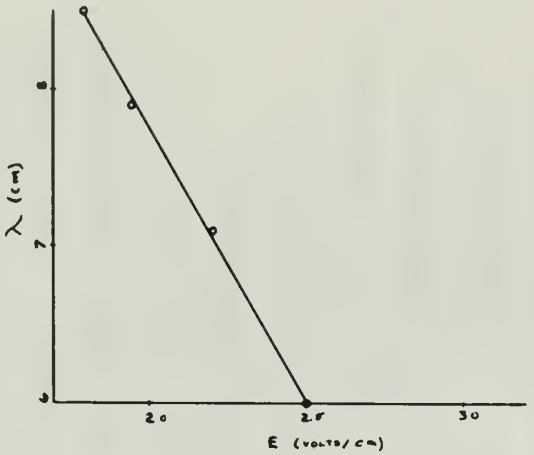



Fig. 29. Plot of striation wavelength versus electric field.

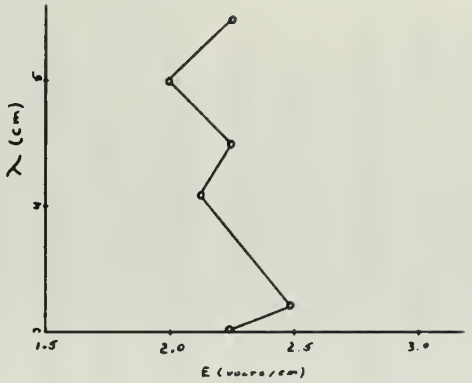



Fig. 30. Plot of striation wavelength versus electric field.



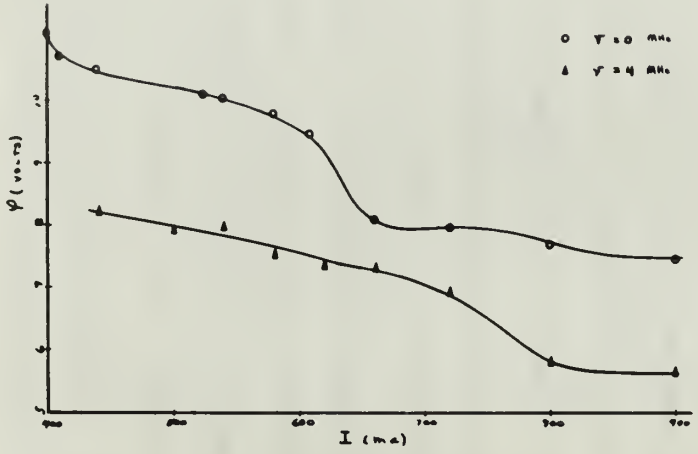



Fig. 31. Plot of $\phi$ versus dc current.

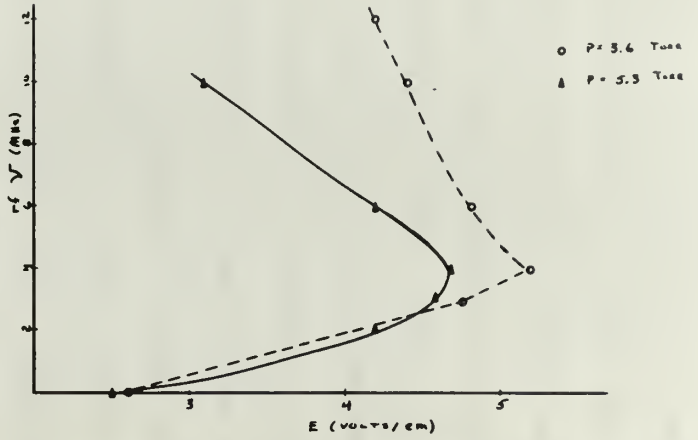



Fig. 32. Plot of rf frequency versus electric field.

level. Due to the non linear properties of the plasma the voltage decrease to accomplish this is not as large as the original voltage increase due to the perturbation. Hence the net effect as seen in Fig. 32 is an increase in electric field. The effect of the rf frequency on the striation wavelength is shown in Fig. 33. It is felt that the transmitter may be partially the cause of the changing effect that seems to take place between 3 MHz and 6 MHz. The TCS-9 transmits less power in this range than in other ranges. The striation wavelength apparently decreases with frequency to a minimum and then increases. The striation frequency decreases as rf frequency increases at lower pressures but at higher pressures the plot is S-shaped as in Fig. 34. Because of the erratic behavior of the frequency and wavelength in relation to the electric field the velocity was plotted against the discharge current. Figure 35 shows that in general the velocity decreases as the dc current increases. The average electron temperature, measured by the double probe method, varied erratically between 1.5 and 3 ev for all values of the dc current and for all values of the electric field as shown in Figs. 36 and 37. As the current was increased the equivalent resistance of the double probe circuit decreased while the ion saturation current and the electron saturation current both steadily increased. This can be seen in Fig. 38 which is a reproduction of X-Y recorder plots. This took place in every run made. However as the electron temperatures were calculated

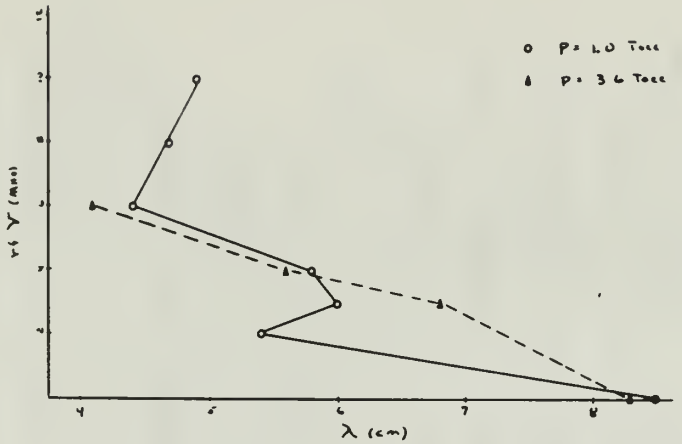


Fig. 33. Plot of rf frequency versus striation wavelength.

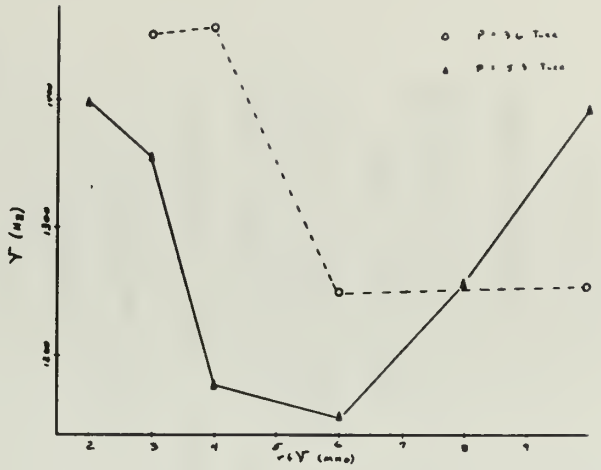


Fig. 34. Plot of rf frequency versus striation frequency.

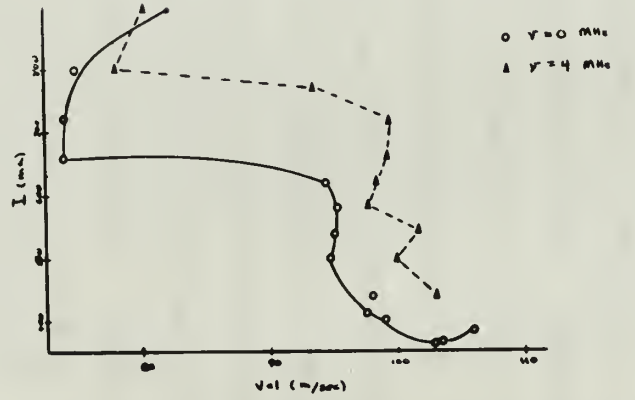


Fig. 35. Plot of dc current versus striation velocity.

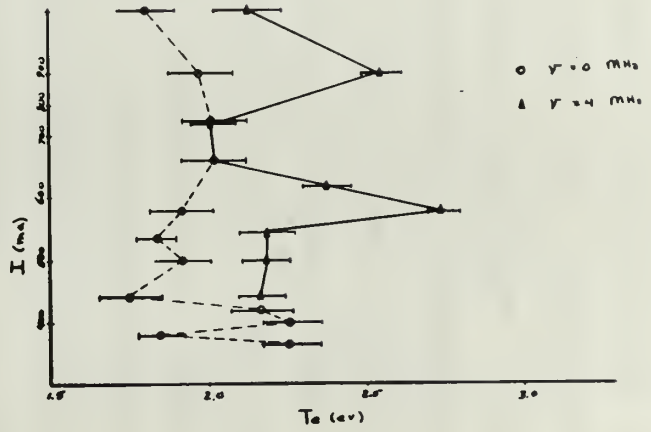


Fig. 36. Plot of dc current versus electron temperature

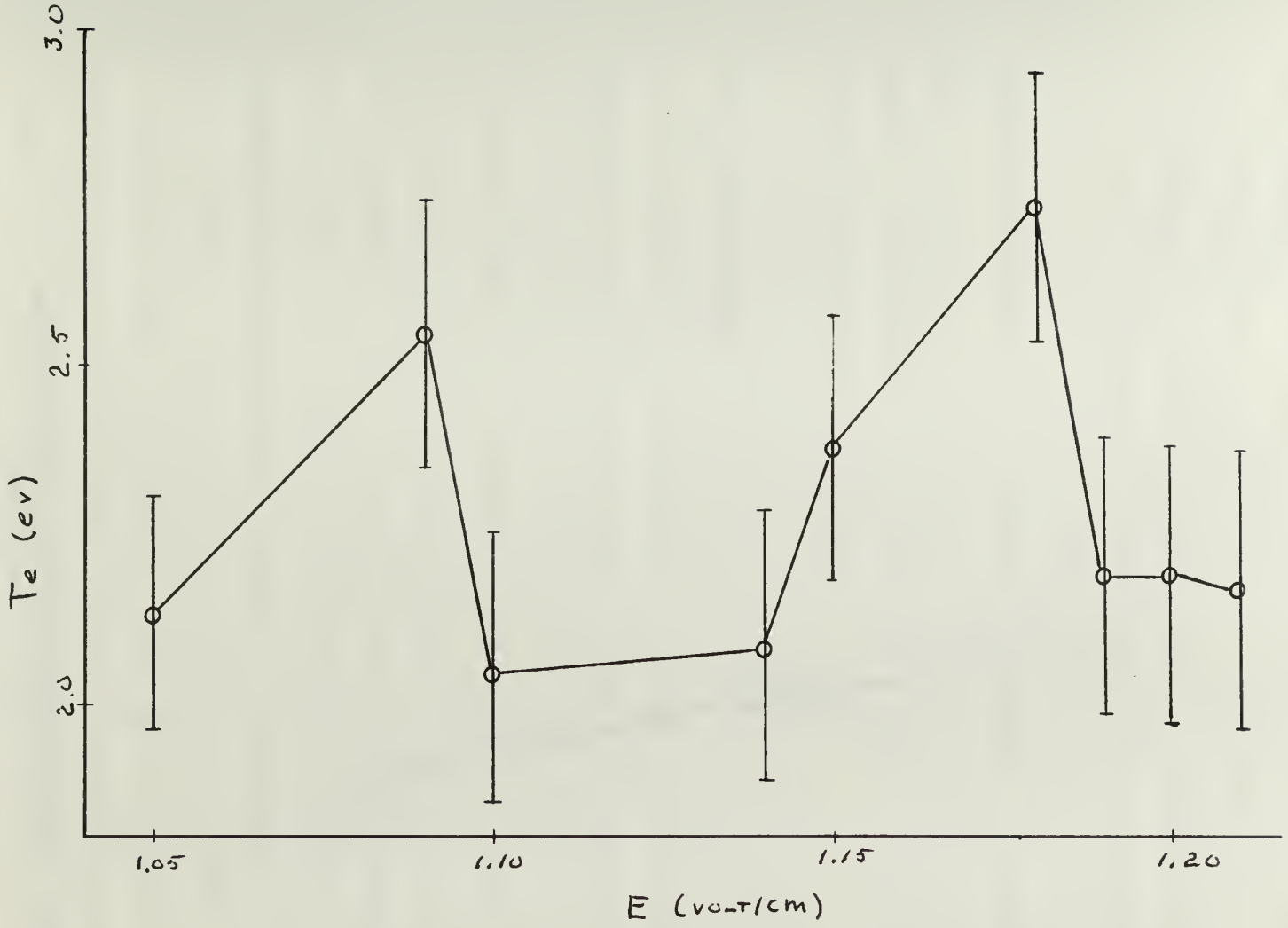



Fig. 37 Plot of electric field versus electron temperature.

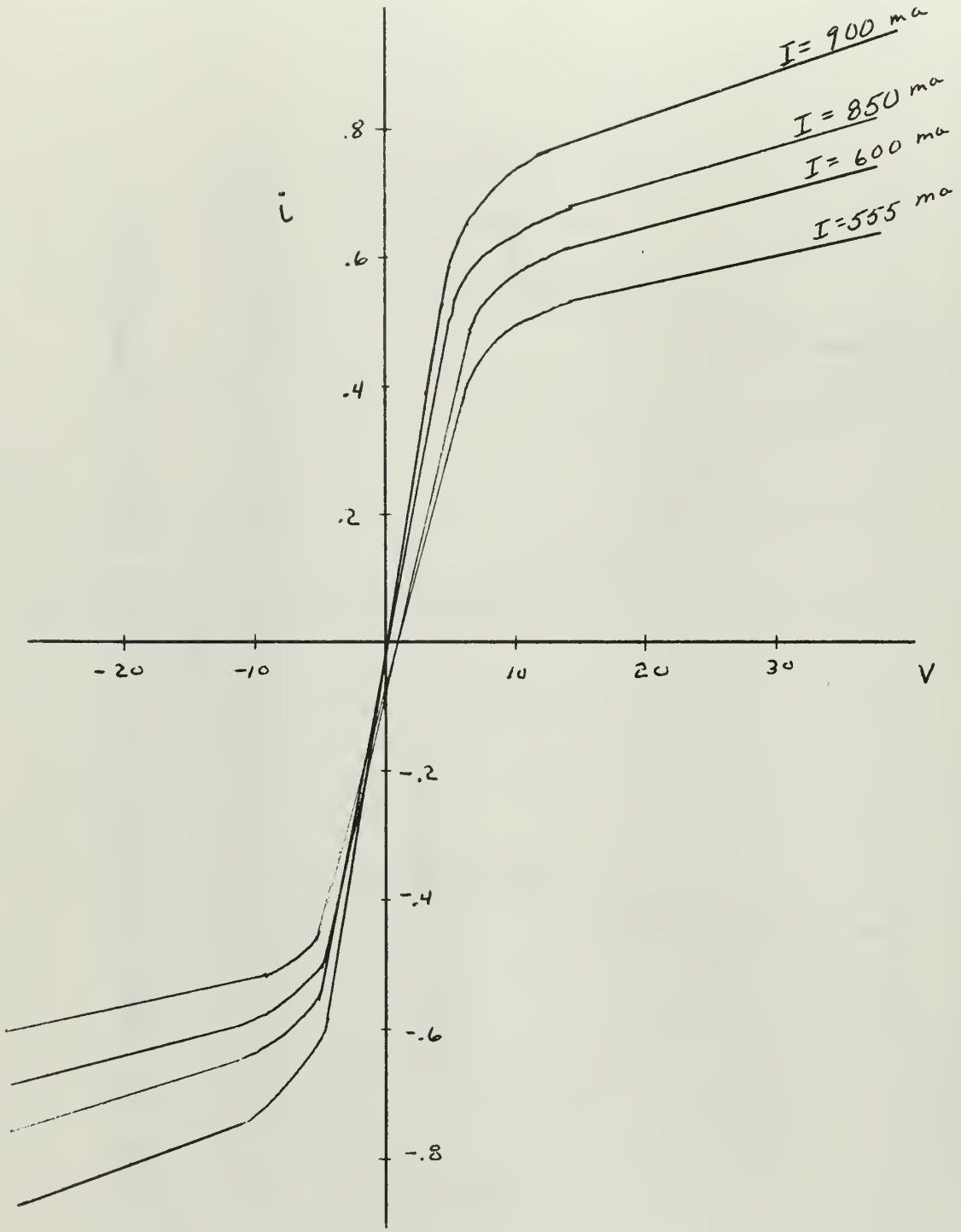



Fig. 38. Probe characteristic curves by the X - Y recorder.

it was discovered that the relationship of these properties to each other in the formula for electron temperature was such that the calculated values were somewhat erratic. All circuits were rechecked to insure proper wiring, connections, etc. The maximum experimental error was determined to be 7% which is not enough to compensate for the fluctuations. The electron temperatures were re-evaluated using the formula derived by Clements [38] . The formula is $Te = \frac{1}{4}R_o\ e/k$. Agreement between the 2 methods was found to be quite good with a difference in most cases of less than 2%. The two methods are equivalent and serve as a check. The agreement is not particularly significant.

4.4 Effects of the rf Perturbation When the Electric Field is Constant

In this set of experiments the general equipment and laboratory set up were the same as those discussed in the previous section. The parameters of a dc discharge perturbed by an rf signal were measured for a range of antenna currents with the electric field held constant. The other parameters were allowed to vary. This was done mainly to evaluate the value of $\phi$ the constant defined by Novak [14] . The experiment was repeated over a range of frequencies from 1.5 MHz to 12 MHz. This process was then repeated for a series of pressures from 1 to 10 torr. This set of experiments was carried out in both tubes shown in Figs. 10 and 11. The parameters measured were the wavelength, frequency, velocity, electric field and electron temperature. An

electrometer was used to measure the potential across two probes 10 cm apart in one tube and 20 cm apart in the other. As discussed in the previous section $\phi$ was found to decrease with an increase in the dc current. In general the value of $\phi$ tended to increase with an increase of the rf power input as shown in Fig. 39. In these experiments the value of $E\lambda$ is not a constant as postulated by Novak [14]. In no case was the relationship a hyperbolic one.

An increase in the rf current seems to show no relation to the wavelength or frequency in that both will fluctuate up and down and stay generally in the same range. The general trend for the velocity is to increase, although fluctuations occur as can be seen in Fig. 40.

The electron temperature fluctuates erratically between 1.5 and 3 electron volts. This phenomenon is exactly that described in the previous section. This behavior can be seen in Fig. 41.

4.5 Effects of the rf Perturbation When the Electric Field and rf Current are Held Constant

This was a short set of experiments to measure the parameters of the moving striations with the dc field and the power input constant. This is a situation where conditions are changed but the basic energy supplied to the glow discharge is held constant. As was the case in previous experiments the relationship $\lambda E$ was not hyperbolic, ie, $\phi$ was not constant. The wavelength, frequency,

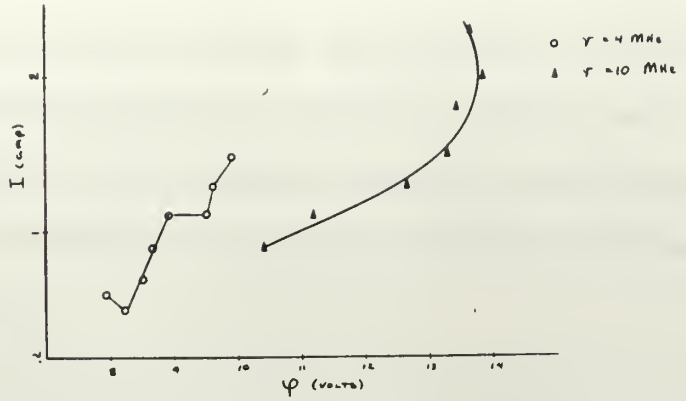



Fig. 39. Plot of rf current versus $\phi$.

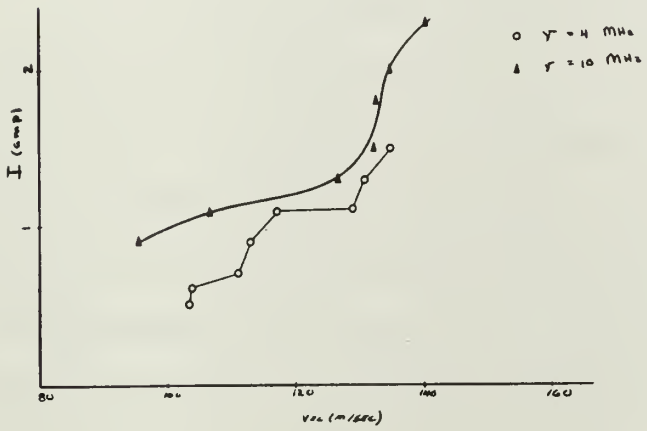



Fig. 40. Plot of rf current versus striation velocity.

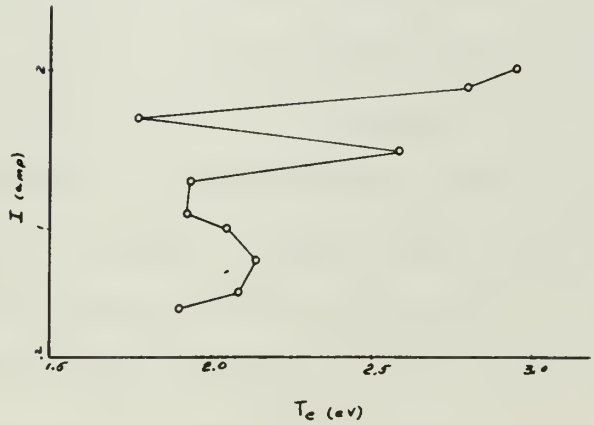



Fig. 41. Plot of rf current versus electron temperature.

and velocity all fluctuated by small amounts staying near one value. The average electron temperatures varied from 2.5 to 3.8 electron volts in the same erratic manner as described earlier and with the same experimental error.

# 5. Conclusions

## 5.1 Conclusions

The conclusions will be listed in three parts to conform with the three research objectives stated earlier in this thesis.

5.1.1 Standing striations are pressure dependent and only exist between certain pressures. The threshold value however is not a sharply defined limit. Standing striations always occur in an integral number, which is dependent on the wavelength and the electrode distance. Since the electrode distance affects the number of standing striations and since the electrode distance apparently has little to do with the parameters that determine wavelength, it is concluded, in agreement with Nakata et. al. [13] , that stationary striations may be standing wave phenomena.

5.1.2 There was no single set of data taken in these experiments in which the wavelength had a hyperbolic dependence on the electric field. The value $\phi$ from the relation $E \lambda = \phi$ decreased with increasing current. The experiment was performed as carefully as possible to insure that there was no perturbation on the system other than that of the rf signal. Under these conditions it is difficult to imagine that the wavelength is uniquely determined by the longitudinal electric field. The conclusion is therefore drawn that the relationship

$$E \lambda = \phi$$

is not valid for all conditions and therefore the electric field is not the basic parameter for the creation of moving striations.

5.1.3 Throughout the course of these experiments the electron temperatures measured were average electron temperatures. The measurements varied in all cases between 1.5 and 3 electron volts. In most cases the variation was erratic. The experimental error was 7% or less in all cases. It was hoped in the beginning that the theoretical relationship between the electron temperature and the electric field could be disproved since it seems likely the electron temperature is dependent on more than the energy supplied to the electrons by the dc electric field. In this experiment, the electron temperatures should depend on more than the energy derived from the dc electric field since the transmitter supplies rf power to the plasma. If the rf input power is held constant, ie, the same amount of energy being supplied by the external source then the relation should still be valid. In these experiments, no relationship between the electron temperature and the electric field was discovered. This is what was hoped for; however, the behavior of the electric temperature in relation to the electric field in the dc discharge (without rf signal) used was erratic. The equivalent resistance, ion saturation current and the electron saturation current all increased with an increase in the current (i.e. a decrease in electric field) but the electron temperature fluctuated. This implies that

there may exist an error in the method or equipment used to evaluate the electron temperatures. The circuits and the theory were rechecked and no such error was detected. The author is unable to explain this error at this time. It is therefore deemed necessary that more experimentation be performed before conclusions are drawn concerning electron temperatures.

5.2 Recommendations For Further Work

It is recommended that further study be made of the relationship between the electric field and the wavelength. To insure that the effects which disrupt the relation $E\ \lambda = \phi$ are not due to external sources it is suggested that these parameters be evaluated under conditions similar to those used by Novak [14] . This could be done by obtaining a homogeneous dc discharge which has no moving striations present. This plasma could then be perturbed by the rf signal and a study could be made of the relationship.

It is further recommended that the electron temperatures be re-evaluated utilizing the methods of Hosea [39] and Garscadden and Bletzinger [40] to get the time resolved electron temperature. The method which involves two oscilloscopes was not feasible in the progress of these experiments due to a lack of the necessary equipment. An attempt was made to modify the procedures used by Garscadden and Bletzinger so that an X-Y recorder could be used to replace one of the oscilloscopes. The attempt was unsuccessful and had to be abandoned due to a lack of time.

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| | Office of Naval Research<br>Department of the Navy<br>Washington, D.C. 20360 |

13. ABSTRACT

A study of striations in the rf glow discharge and the dc discharge with rf perturbations was conducted in neon gas over an rf frequency range of 1.5 MHz to 12 MHz and a pressure range of 1 to 15 torr. The striation parameters were measured in a variety of situations and a study was made of (1) stationary striation phenomena, to include the parameters of the rf discharge, the effects of the induced rf electric field and the limitations imposed by the power input to the field, (2) the relation between the striation wavelength and the longitudinal electric field and (3) the relation between the electron temperature and the longitudinal electric field. The utilization of an rf perturbation allowed a study of rf discharge phenomena and gave a method whereby power could be put into the discharge by a means other than the dc electric field. The results of the experiment indicate (a) that stationary striations may be a standing wave phenomenon (b) the wavelength of moving striations is not uniquely determined by the electric field (c) more work and analysis is necessary concerning the relationship of the electron temperature and the longitudinal electric field.

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UNCLASSIFIED

Security Classification

| 14. KEY WORDS | LINK A | | LINK B | | LINK C | |
|---|---|---|---|---|---|---|
| | ROLE | WT | ROLE | WT | ROLE | WT |
| Neon | | | | | | |
| Moving Striations | | | | | | |
| Stationary Striations | | | | | | |
| rf Discharges | | | | | | |
| Plasma Oscillations | | | | | | |

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